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2nd International Workshop on Design in Civil and Environmental Engineering

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Organized and Sponsored by

Worcester Polytechnic Institute
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Technical University of Denmark
Fraunhofer USA, Center for Sustainable Engineering
Massachusetts Institute of Technology

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Foreword

The desire and ability to shape the world around us are two of the characteristics that define humanity. The complex structures, systems, and infrastructure that have been created through the collective efforts of past and present generations are truly wonderful accomplishments. However, the built environment must be maintained and expanded to sustain and improve the quality of our lives. To do so while protecting the natural environment for future generations presents an enormous challenge to engineers. This effort will require collaboration with actors in many fields to address the technical, social, economic, and environmental issues that are involved in such an undertaking.

The civil and environmental engineers of tomorrow need to be prepared to design and implement creative and innovation solutions in multicultural and multidisciplinary teams and contexts. This means that the civil and environmental engineers of today need to develop a strong understanding of both disciplinary and interdisciplinary design processes, to identify gaps in our current understanding so these can be addressed by design researchers, and to improve design education so this knowledge can be shared with those who will need it most.

The 2nd International Workshop on Design in Civil and Environmental Engineering followed a successful workshop hosted by KAIST in 2011 where participants from the US, Europe and Asia discussed the need for design as a discipline in civil and environmental engineering, explored the state of the art in design research and education in CEE, and provided insight into civil design from the perspectives of architecture and mechanical engineering. This year’s workshop built on that foundation to clearly define the most promising areas for design research, the challenges of civil design, the need for interdisciplinary collaboration, the opportunities for knowledge exchange with other design disciplines, and the advancements being made in civil design education.

DCEE 2013 featured 19 technical presentations by researchers from Bangladesh, Belgium, Denmark, Italy, Papua New Guinea, Taiwan, the United Arab Emirates, and the United States. The presentations spanned all aspects of civil and environmental engineering including architecture and architectural engineering, building technology, construction management, geotechnical and materials engineering, structural design, sustainability, urban planning, and water resource management. Together, they viewed civil design from the combined perspectives of research, practice, and education at all length scales from micro to mega.

DCEE 2013 included a technical tour of the new Fraunhofer USA Center for Sustainable Engineering headquarters in Boston and laboratory tours hosted by the MIT and WPI Civil and Environmental Engineering Departments. The meeting concluded with two working group sessions that addressed issues associated with design research and education in CEE.

Many thanks are due to all of the authors, presenters, and participants of the workshop for sharing their research, ideas, and experiences. Their insights and enthusiasm helped to make the meeting a great success. Thanks are also due to our local organizing committee and to the international program committee members for their assistance with conference preparations; to Dr. Kurt Roth for hosting the technical tour of Fraunhofer CSE’s new headquarters in Boston, to Prof. Herbert Einstein and Prof. Tahar El-Korchi for hosting the tours of the MIT and WPI Civil and Environmental Engineering Department facilities; and to

Ms. Irene Paradisi for her tireless efforts for the workshop. From both a logistical and scientific perspective, this workshop would not have been possible without her. Finally, we would like to thank Worcester Polytechnic Institute; the Fraunhofer Italia Innovation Engineering Center, the Technical University of Denmark, Fraunhofer USA's Center for Sustainable Engineering, and the Massachusetts Institute of Technology for their support of the workshop.

We are looking forward to the 3rd International Workshop on Design in Civil and Environmental Engineering which will be held at the Technical University of Denmark in August, 2014. We very much hope that you will join us for the continuation of this interesting and important discussion and support the continued effort to establish design as a discipline within civil and environmental engineering.

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September 20, 2013

Table of Contents

Construction and Materials Design and Engineering

Design Education in Civil Engineering and Related Fields

Results and Recommendations

Challenges and Opportunities for Establishing Design as a Research Discipline in Civil and Environmental Engineering

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Abstract: There are a number of fields including architecture, industrial design, and urban planning and design, where design is the discipline upon which all research and teaching activities are based. In other fields such as aerospace and mechanical engineering, design is a sub-discipline with its own faculty, research and education communities, conferences, and journals. However, design remains an emerging sub-discipline in civil and environmental engineering – practiced, valued, and taught but not subject to rigorous academic research. This paper presents some of the challenges associated with the establishment of design as a research discipline within civil and environmental engineering, some of the benefits and opportunities that will come from that establishment, and some evidence for the fact that this process has already begun.

Keywords: Design, Research, Education, Civil and Environmental Engineering.

Introduction

There are a number of fields including architecture, industrial design, and urban planning and design, where design is the discipline upon which all research and teaching activities are based. In other fields such as aerospace and mechanical engineering, design is a sub-discipline with its own faculty, research and education communities, conferences, and journals (Thompson 2011).

In civil and environmental engineering, design is a valued and integral part of civil engineering practice. It is an increasingly common and important part of education in CEE. And there are outlets, including the Journal of Engineering Design and Research in Engineering Design, which accept and publish research papers related to civil design. However, design is not yet a fully established research discipline with dedicated faculty, journals, conferences (or conference tracks), and qualifying exams.

This paper presents some of the challenges associated with the establishment of design as a research discipline within civil and environmental engineering, some of the benefits and opportunities that will come from that establishment, and some evidence for the fact that this process has already begun.

Multiple Types of Knowledge are Required for Engineering Design

The first challenge associated with establishing design as a research discipline is the fact that design activities require multiple types of knowledge, including but not limited to: design knowledge, domain knowledge, and knowledge about the problem to be solved.

Design Knowledge

Design knowledge includes information about various design tools and processes, their uses, and how they can be modified for specific applications. It addresses the nature of technical artifacts, the interactions between various elements within an artifact, and how an artifact's performance and characteristics change over the life cycle. It also focuses on the humans who create and interact with artifacts and how this interaction influences the design requirements, the generation of design concepts, the success of an individual artifact, and the evolution of technology in general. Some of this knowledge can be, and historically was, learned through experience. However, the goal of most design research is to develop, formalize, and validate this knowledge to improve the efficiency of the design process and the quality of the resulting artifacts.

Domain Knowledge

Domain knowledge refers to the knowledge and skills associated with the (technical) domain(s) that will be used to create the artifact. It also includes information about the environment(s) in which the artifact will function. For example, structural design requires an understanding of mechanics, materials, vibration and dynamics. Similarly, geotechnical design requires an understanding of soil mechanics, rock mechanics, hydrology and geochemistry.

Problem Knowledge

Finally, designers need a strong understanding of the specific problem that an artifact is intended to solve. Every design task involves different stakeholders, requirements, and constraints. This is particularly true in civil and environmental engineering, where every construction site has different properties and conditions. For example, the design of a bridge in a seismically active area will be substantially different from one that will be built in a region with few active faults. Similarly, the design of water resource management systems strongly depends on the local climate and the existing infrastructure.

The Relative Importance of Design, Domain and Problem Knowledge

The importance of domain knowledge relative to design knowledge is part of what separates engineering design from other design fields where design is the discipline. In the more "designerly" (Cross 2007) disciplines where form, emotion, and human interaction are emphasized, it is common for one set of individuals to develop the design concepts, for another to do the detailed design, and for a third set to produce the final artifact. This reduces the domain knowledge required by the designers and allows their training to focus almost exclusively on design knowledge. Thus, design becomes the discipline.

In engineering design, the root cause of the problem to be solved is usually technical in nature. Function often dominates other considerations. And, form and function usually cannot be separated. Thus, the designer needs strong domain knowledge to understand and define the design task and to propose concepts that can realistically address it. In addition, the design and production of the artifact often cannot be separated. This means that the designer either needs to be well versed in manufacturing (or construction) or needs to work closely with individuals who have expertise in those areas.

The importance of domain knowledge in engineering design means that these types of problems often can only be addressed by an engineer. This, combined with a lack of awareness, understanding, and appreciation of design knowledge, may be one of the reasons that design in civil and environmental engineering has typically been housed within the various silos of technical knowledge (structural engineering, geotechnical engineering, etc.) where expertise is narrow and deep (figure 1) rather than being an independent discipline where expertise is shallow but wide (figure 2).

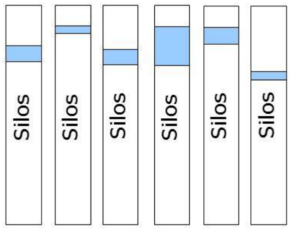

Figure 1. Design Housed within the Disciplines of Civil and Environmental Engineering

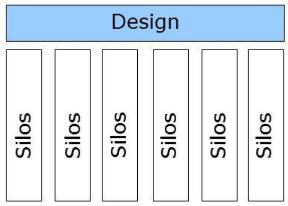

Figure 2. Design as a Sub-Discipline within Mechanical Engineering

Engineering Design is Located at the Intersection of Multiple Diverse Disciplines

The second challenge associated with the establishment of design as a research discipline is the fact that design is an interdisciplinary – and sometimes multidisciplinary – activity with domain boundaries that are often both porous and transparent.

For example, in mechanical engineering, design research generally focuses on product design, machine design, and system design. (Other types of design including material and process design are also done but generally receive less emphasis in both design research and education.) Within mechanical engineering, these areas are most closely associated with the 'harder' subjects of mechatronics, controls, and manufacturing. They also share borders with 'softer' subjects outside of engineering such as industrial design and engineering management (figure 3). This has led to a division of mechanical design into two communities: one with strong ties to manufacturing and production and the other with management and industrial design.

When viewed in the same manner, civil design can be thought of as having two main areas: structural design (bridges, buildings, dams, etc.) and system design (transportation systems, water resource management systems, etc.). Since system design is common to all systems, this forms a strong link between mechanical and civil design. On the 'softer' side, civil design is linked to architecture and urban planning, which are, in turn, linked to other 'designerly' fields such as industrial design and landscape design. Construction management and engineering has a similar relationship to civil design as manufacturing does to mechanical design.

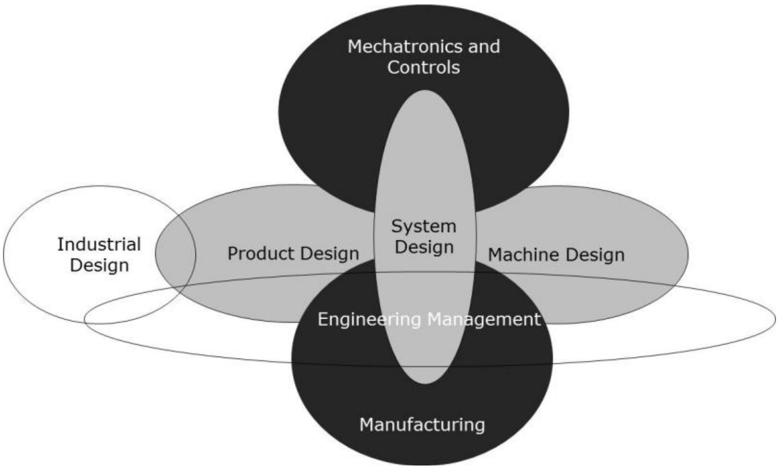

Figure 3. Design in the Field of Mechanical Engineering

These tightly coupled relationships give engineering design researchers more opportunities to publish their work because it can go to design journals, the technical domain journals, and journals associated with the final application. However, they also make it difficult to distinguish engineering design from the older and better established fields that surround it. This, in turn, makes it difficult for engineering design researchers to clearly define their expertise and thus to obtain tenure and other academic recognition.

Design Research, Practice, and Education Are Coupled

The third challenge stems from the interconnectivity of design research, practice, and education. Traditionally, engineering design was either done by individuals who had an intuitive understanding of technological artifacts and an innate ability to develop them, or by individuals who learned design through a combination of apprenticeship and experience. This model of design education was the de facto standard through the first half of the 20th century and continues to be used around the world today.

Although the apprenticeship and experience model can be an effective way to train designers, it depends almost entirely on the knowledge and skills of the master, and on his or her ability to convey that information. Mastery was, and often still is, achieved because of a natural talent for design. That talent is not necessarily accompanied by an ability to explain how and why design is done in a way that will allow others to replicate the master’s success. In the absence of high quality instruction (and/or external sources of information like design textbooks), design students must rely on their own experience, intuition, and trial-and-error methods. This usually leads to a less efficient design process, increased bias, more design errors, and a lower probability of success.

The fact that design can be done without rigorous training, a formal design process, and/or an understanding of design theory and methodology is often used to argue that formal design knowledge is unnecessary and that design cannot (or should not) be taught. However, the high failure rate of new companies, technologies, and systems is a clear indication that there is still much to be learned about engineering design.

Modern design education varies by field. The more designerly disciplines such as architecture and industrial design teach design through a combination of history, case studies, design practice in a studio environment, and dialogue with professional designers. In contrast, leading engineering design programs combine design theory and methodology with design practice that usually culminates in a simulation or build-and-test verification step. In both cases, the challenge is that design education requires the faculty to teach the students how to do (and identify) ‘good’ design – something that is not well understood and generally not agreed upon by researchers and practitioners in the field. For this reason, design education is, and must be, informed by design research (in addition to design history and design practice).

At the same time, design researchers rely heavily on classroom settings to study design students as they apply new tools and methods to a wide range of problems and to identify the shortcomings of current design knowledge. The result is that engineering design researchers often move fluidly between the engineering and engineering education domains and their associated conferences and journals. This brings an important added benefit; design education researchers are able to bring back other contributions from the educational research community (pedagogical methods to improve content delivery, increase participation and retention, strengthen team work, improve assessment, etc.) that can inform and improve engineering education in general.

There is plenty of evidence that design education is increasingly valued and included in both traditional and non-traditional civil and environmental engineering curricula and that research in civil design education is being done (Benedetti *et al* 2013; Einstein 2013; Jensen and Almegaard 2011; Ni *et al.* 2011; Solis *et al.* 2012, Wu *et al*. 2011). However, the role of design research in informing and improving design education is only starting to be seen and appreciated.

When and How to Specialize in Engineering Design?

These three challenges raise important questions about how and when to specialize in engineering design. If we accept that all engineering designers must have a solid foundation in the engineering fundamentals, then it stands to reason that undergraduate students should focus on at least one of the traditional technical silos rather than pursuing a design specialty early in their careers. To do otherwise carries the risk that the students will not be true engineers when they graduate, but rather generalists with some exposure but no disciplinary expertise in either design or engineering. The importance of the engineering foundation is clear in light of the fact that all of the great engineering design theorists of the 20th century had strong technical backgrounds (in manufacturing engineering, computer science, cognitive psychology, etc.) that influenced their contributions in the design domain. This also implies that design education that focuses on engineering practice and the design process at the undergraduate and master's level may be different from education that prepares students to perform interdisciplinary design research at the doctoral level.

Opportunity for Exchange of Design Knowledge Between Domains

The fact that design serves as a cross-roads for different domains and disciplines means that there is great opportunity for the transfer of knowledge between CEE and other design-related fields. Design, and thus design research, depends on a number of factors including:

- The type of artifact to be designed (product, machine, system, structure, etc.)
- The physical and technical domains involved
- The size and complexity of the artifact
- The number and nature of the stakeholders involved in the design process
- The number of artifacts that will be required or produced
- The desired or required level of novelty (routine, adaptive, variant, innovative, creative, radical, etc.)
- The phase of the design process (problem specification, conceptual design, system level design, detailed design, embodiment, validation, repair and maintenance, etc.)

Mechanical engineers typically design small to medium sized artifacts for mass production. In contrast, civil engineers typically design large (mega scale) custom artifacts for populations with a large number of stakeholders who have conflicting requirements. This means that there is great potential to expand our understanding of design by applying existing design theories and methodologies from mechanical engineering to the civil domain. And, there is much that has already been learned in other design domains that can be taught to teach the civil design community.

Opportunity for Maximum Impact

Most of the great challenges of the 21st century are tied more strongly to civil and environmental engineering than mechanical engineering. These challenges include:

- Energy independence
- Environmental sustainability
- Availability of clean water
- Climate change
- The evolution of the built environment
- Aging infrastructure in more developed nations
- The rapid development of less developed nations

Thus, the greatest potential for designers and design researchers to have a positive impact on society will be in the realm of civil and environmental engineering rather than in mechanical engineering.

The Process Has Already Begun

There is substantial evidence that interdisciplinary exchanges between mechanical design and manufacturing and civil design and construction management are taking place and have been for some time. From a practical perspective, the concepts associated with lean manufacturing (Jones and Roos 1990) were rapidly adopted by the construction management industry (Ballard and Howell 1994). Similarly, additive manufacturing (Kruth *et al.* 1998) was quickly adapted for the construction industry (Khoshnevis 2004). From a more theoretical perspective, Axiomatic Design Theory (Suh 1978, 1990, 2001) is increasingly being used in architectural, building, and structural design (Albano and Suh 1992; Pastor and Benavides 2011; Gilbert *et al.* 2013; Marchesi *et al.* 2013), urban planning (Monizza *et al.* 2013), transportation (Baca *et al*. 2013, Thompson *et al.* 2009a; Thompson *et al.* 200b; Thompson and Doroshenko 2010; Yi and Thompson 2011), water resource management (Ibragimova *et al.* 2009; Pena *et al.* 2010), and construction management (Dallasega *et al.* 2013). These exchanges have not only led to new insights into the civil design process, they have also highlighted the limitations of existing design theories and identified opportunities to improve and expand those theories. This will ultimately pave the way for a more universal understanding of design and establish design as the "science of the artificial" as Herbert Simon (1969) intended.

Conclusions

Although a small community surrounding design research and education in civil and environmental engineering has begun to form, it is important to provide a forum where researchers from civil and environmental engineering can discuss design research in a supportive and interdisciplinary environment. The Second International Workshop on Design in Civil and Environmental Engineering is intended to provide that support and to help its participants lay the foundation for a civil design research community that will improve our understanding of engineering design and design education in civil and environmental engineering and beyond.

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Design of the Building Execution Process in SME Construction Networks

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Abstract: While the implementation of lean management methods in the automotive and aerospace industries is common nowadays, the architecture, engineering and construction (AEC) industry is lagging behind in this development. Up to now, research in construction has been focused on product development, while improvement in organizations and processes has been almost ignored. This paper describes an innovative methodology for planning the building execution process, called Integral Building Execution Planning (IBEP), which is suitable for construction networks composed of small and medium sized enterprises (SMEs). The IBEP approach is part of a new production system in construction with the aim to improve process reliability during the execution phase by integrating actors from implementation into planning. The design methodology IBEP was developed within the research project "build4future", especially by reengineering two completed projects with their participating key actors.

Keywords: Just in Time, Engineered to Order, Last Planner System, Process Reliability, Small and Medium-Sized Enterprises.

Introduction

The building sector in the Province of Bolzano is one of the key industries for the local economy and one of the largest economic branches in Italy and Europe. However it is composed of SMEs that struggle in price competition with the globalized market. The research project build4future (Matt *et al*. 2011) was launched to develop an intelligent approach to planning and construction that would eliminate sources of waste in the AEC industry and support local SMEs.

Traditionally, construction project managers have assigned unreliable time schedules without any on site capacity planning which could not be followed by their crews. In a conventional value chain composed of different companies, a delay in work completion by one enterprise affects the downstream activities of the following companies. Since supplier lead times are, for the most part, much greater than the possible accurate foresight regarding work completion, a just in time (JIT) delivery of Engineered to Order components from production to the construction site is not possible.

Recent research studies have shown that a potential cost saving of 30% could be reached by implementing lean processes (Cain 2004). Moreover, from the practical side, a recent survey estimated a potential cost saving of between 11% and 20% by optimizing construction processes (Krause *et al.* 2012). This confirms the fact that research in construction is needed and that cost savings estimates in research correspond to estimates from practitioners.

This paper is related to the second phase of the b4f project and focuses on the development of a method to optimize the planning process for building execution. For this purpose, two existing buildings were analyzed in order to develop a new production system based on lean concepts from other production sectors.

State of the Art

Owners often commission architectural design and construction separately, so working relations between architects/engineers, contractors and subcontractors vary on a project by project basis (Lincoln and Syed 2011). Due to these changing customer-supplier relationships, the requirements of the involved crafts are unknown among the participants. This often causes high coordination costs in construction projects. Furthermore, in Italy the construction industry has become highly specialized which increases the number of interfaces in a construction project. Every participating trade tries to optimize its own production and installation process without considering their influence on the overall construction process. All AEC clients seek major reductions in the cost of buildings. However, this can be achieved only by an integration of design and construction as seen in other engineering sectors (such as the automobile and manufacturing industries) (Choo *et al.* 2004).

Planning and management of the design phase requires planners to take into account the iterative nature of the process and the changing needs of the project stakeholders (Choo *et al.* 2004). The construction sector is characterized by high variability like the changing availability of resources, differing legislative frameworks, a lack of information, unpredictable weather conditions, and so on. Ballard developed the Last Planner® System (LPS) to surpass and optimize the traditional method of construction management during the execution phase (Ballard 2000). He revealed that variability is the major source of waste in construction. The "last planner" is the last in the decision chain of the organization because the output of his/her planning process is not a directive for a lower level planning process but results in production. The last planner only releases workable jobs to the field, as opposed to the traditional practice of pushing assignments onto construction crews in order to meet scheduled dates (Kim *et al.* 2010).

Traditionally, project management tools address what SHOULD be done to meet a master schedule or Critical Path Method (CPM) schedule, as opposed to verifying what CAN be done. Decision makers often lack the ability to ensure that scheduled work is within a crew's capability (Lincoln and Syed 2011). Time schedules are usually elaborated without taking into consideration the number of workers needed on site. This means that scheduled work packages are not kept and delays in work completion occur. Moreover, time schedules are not continuously updated and therefore cannot be used as a tool for coordinating the involved actors during a building project. Research in the lean construction community has shown that work flow reliability must be achieved as a prerequisite to managing costs and schedules (Ballard and Howell 1998; Howell 1999).

Koskela (2000) defines a theory as something that explains observed behavior and contributes to the understanding and prediction of future behavior. It has been argued that construction does not have an explicit theory (Koskela 2000; Koskela and Howell 2002). On the other hand, by verifying this statement, one approach was identified which goes partially in the direction of defining a theory. The Metra Potential Method (MPM) was developed in 1958 by the company SEMA and was used for the first time for the construction of nuclear power plants on the Loire (Burghardt 2006). The MPM is a network planning method of the "activity on node" type. In MPM, activities are represented by bars and relations are represented by arrows. In the Extended Metra Potential Method (EMPM), different types of relations (begin-begin, begin-end, end-begin, end-end, percentage) were introduced, as well as negative arrows and cycles. Furthermore variable activity durations suitable for the construction industry were introduced (Kerbosch and Shell 1972). Kerbosch and Shell (1972) stated that they used and tested EMPM in the building industry on different projects concerning planning and project control reaching satisfactory results.

In the manufacturing industry, releasing large batches of work to the shop floor causes several problems. A large volume of work typically occurs over time and it is difficult to monitor the production progress. In addition, this makes responding to changes in customer requirements very complicated (Rother and Shook 2009). The same also applies to the construction sector. Establishing a constant production pace could create a predictable construction flow that would enable quick correction action to be taken in case of unforeseen problems. In Lean Manufacturing, the consistent amount of production instructions released at the pacemaker process and simultaneously the taking away of an equal amount of finished goods is called "paced withdrawal" (Rother and Shook 2009). This consistent increment of work is called "Pitch" and is calculated by multiplying the number of parts a finished goods container holds by the "Takt Time" needed for producing one part (Rother and Shook 2009). This "Pitch" becomes the basic unit of the production schedule for the considered product family.

In construction, unlike the manufacturing industry, the building (product) does not move along a production line but, rather, crafts (workers) move from one construction section to the next. So, the challenge is to synchronize the different crafts within the construction sections to meet the delivery date.

Kenley (2005) states that site confusion generally arises from traditional planning systems that provide a plan to the site which cannot be executed. "Construction is the production of a complex, one-of-a-kind product undertaken mainly at the delivery point by a series of repeating but variable activities in multiple locations within a multi-skilled ad-hoc team" (Kenley 2005). Unlike production, construction is organized around discrete activities which are organized in sequence but not by location. To prevent traditional ways of construction disruptions, Kenley suggests a location-based planning system (i.e. a flowline). However, Kenley argues that a flowline requires that construction activities have to be aligned to prevent an extension of the contract duration or a disturbance in the workflow (Kenley 2005).

Yu *et al.* (2009) designed a production flow and synchronized it to the Takt Time in the home building industry. They argued that applying just lean production tools, like the supermarket-based pull flow, for reaching a reliable working process doesn't work in construction. Therefore, they proposed a FIFO-lane-based flow system based on the Last

Planner methodology. The mentioned system is based on the so called “Heijunka Box”. The aim is to stabilize and reduce lead time by guaranteeing trade contractor’s working load, using agreed capacity between a home builder and its trade partner on the number of jobs that a subtrade will perform each week (Yu *et al.* 2009). As a result, Yu showed in the paper that the total construction duration could be reduced by about 41 percent, the waiting time could be reduced by about 11 percent, and the value added ratio could be increased from 17 to 26 percent (Yu *et al.* 2009). Furthermore, the FIFO-lane based flow was tested with 15 houses that passed through the system which showed that the process variability was significantly reduced.

The PRECISE Production System

An essential prerequisite for success in complex construction projects is that architects and specialist planners have access to information from executing companies and suppliers. In the manufacturing industry this concept is called “frontloading”. However, in the AEC sector, contractual and public procurement law requirements, diverging project objectives, and a lack of process understanding impede an early and interdisciplinary collaboration.

The PRECISE production system was developed as part of the research project b4f in collaboration with 12 South Tyrolean companies. PRECISE is the acronym for Process REliability in ConstructIon for SmEs. This innovative production system integrates different lean management strategies that are suitable for the construction industry in order to achieve process reliability within networks of SMEs. Partnering also plays an important role. Two or more companies collaborate within different projects based on confidence, dedication to common goals, and an understanding of each other’s individual processes, requirements and values. The implementation of lean management principles in construction cannot be effectively done without having the prerequisite of partnering. The PRECISE production system consists of three phases (figure 1):

1) In the Early Interdisciplinary Building Design phase, the project award and the foundation of the project consortium take place as soon as possible. This allows key actors from both planning and execution to evaluate and optimize the building design taking into consideration relevant aspects like: accessibility, constructability, durability, affordability and so on. As a result, an integration of product- and process design can successfully be done in this early stage.

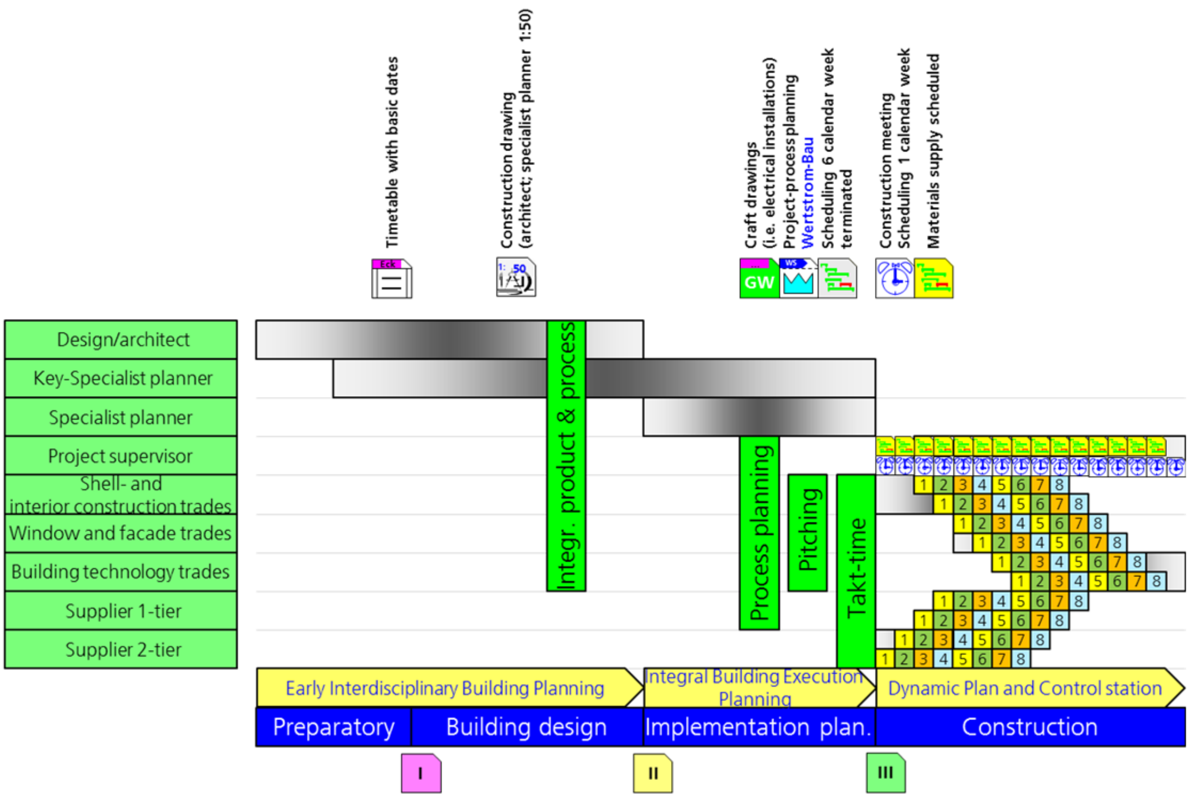

Figure 1. The PRECISE Production System (Schweizer 2012)

2) In the Integral Building Execution Planning (IBEP) phase, a process plan for the operations on the construction site is developed by the companies responsible for executing the work and their key suppliers in collaboration with the design actors. Here, one “neutral” actor without economic interests in the project, should moderate the workshop in order to develop the process plan. This actor should have the capability to extract relevant information from the participants in an efficient way. This workshop should not take more than half a working day and should not put undue strain the company’s time budget. In this phase, the Pitching concept is applied in order to synchronize all actors on site and to reach a constant work flow. The basic unit of the production schedule is set at one day or one week. Moreover, for integrating first and second tier suppliers the Takt Time principle derived from the manufacturing industry is used.

3) To implement the innovative execution planning approach (as described in the previous paragraph) a dynamic planning and controlling tool called “Dynamic Control Panel” was developed. This system should be accessible to all actors at the construction site and support the daily coordination of all involved crafts.

Using the analogy to industrial production, the PRECISE production system is interpreted as work plan for realizing the product, which in this case is the building.

Case Study – Process Reengineering

Within the build4future project, a reengineering of two completed projects was done in collaboration with the participating actors: the architect, the project supervisor and some execution companies and suppliers. The PRECISE production system was used as a guideline, especially the Integral Building Execution Planning (IBEP) approach. The objective was to improve current performance by continuous improvement. To abstract scientific findings from analyzing specific scenarios, process models were created by taking into account existing restrictions.

Traditionally, time schedules are created using a so called push methodology. This means that the planning actor directs (pushes) the duration of the working tasks. In the IBEP approach, execution companies determine the task sequence and the work content in collaboration with the planning actor. Integrating the companies that are responsible for the execution into the planning process allows high workflow reliability to be reached.

Project Scenario 1 – Hotel 3.0

In the year 2008, the architectural studio Ralf Dejaco (b4f project partner) developed the building design and was responsible for the construction supervision of a hotel-expansion project with an overall cost of around 3 million Euros. The extension project consisted of twelve double rooms in the second basement level, twelve double rooms in the first basement level, an outdoor and indoor heated swimming pool, a new wellness area, and the expansion of the dining area.

Project Scenario 2 – Logistic Center 30.0

In the year 2009, a new logistics center for meat products with an overall cost of around 30 million Euros was constructed close to Bolzano, Italy. Here the b4f partner company Expan GmbH, which supplies light weight construction systems, was responsible for installing the industrial panels.

Case Study Procedure

The participating trades were divided in three different subgroups resulting in three different workshops: 1) trades concerning the core process construction (shell and interior construction); 2) trades concerning windows and facades; and 3) trades concerning the building technology.

Step 1: Process Planning

The step “process planning” starts with the division of the building into construction sections. This is done to reach a higher parallelization and to balance existing capacities in terms of available resources. When using traditional software tools for project management, like MS-Project, the network plan results from the time schedule. On the other hand, when using the IBEP-methodology, time scheduling is based on network planning. In this work, the MPM methodology was used. An appropriate activity sequence and duration was determined by focusing on the optimization of the whole process and not just individual processes.

Step 1.1: Development of Construction Sections

First, an interdisciplinary team (figure 2), divided the buildings into construction sections. The hotel building (figure 3) was divided into: 1) the rooms section; 2) the corridor area; 3) the engineering room (for wellness and swimming pool); 4) the swimming pool section; 5) the terrace area; 6) the dining room expansion, and 7) the roof of the dining expansion. Every section corresponds to a respective level (i.e. rooms second and first basement level, etc.).

The corridor area was considered separately from the rooms section, because it represents a kind of bottleneck. Different trades have to pass through it and work on it simultaneously.

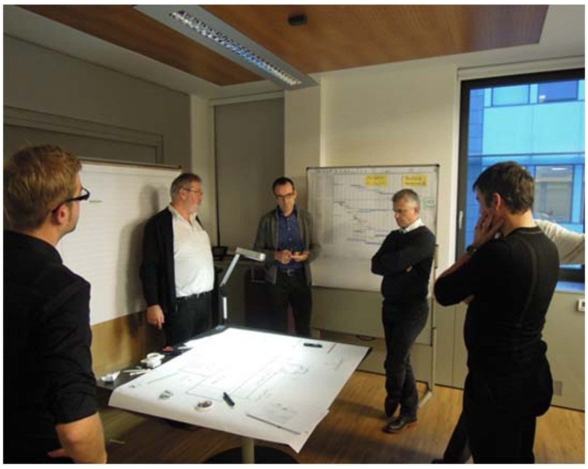

Figure 2. Interdisciplinary Process Planning Team

Figure 3. Construction Sections of First Basement Level – Project 1 Hotel 3.0

Looking at the project scenario of the logistics center, a wider range of construction sections occur (figure 4). In addition, they change over the course of the project. For example, during the shell construction the application hall (NA) and the deep freezing store (TK) are considered as one main area, whereas during the interior construction they are considered separately because they contain a different type of technology.

After defining the construction sections, the job content in every section was estimated by the participating actors (REFA 1993). Job content means in this case the work type and the amount of work in terms of hours and number of needed resources.

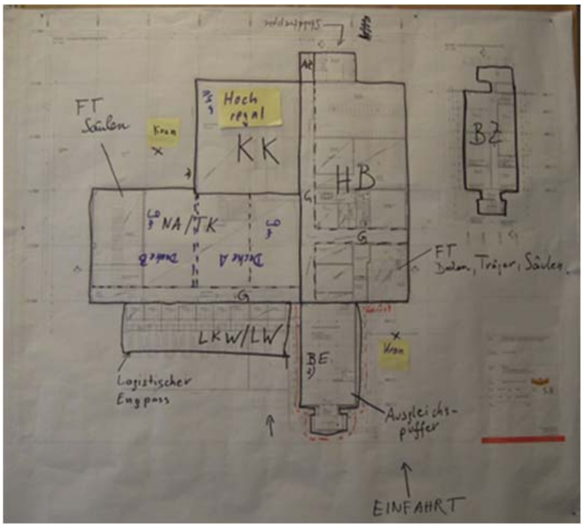

Figure 4. Construction Sections Ground Level Project 2 Logistics Center 30.0

Step 1.2 Elaboration of the Network Planning

Within the process reengineering a new methodology for network planning was developed (figure 5). For every task, suitable information, like the responsible craftsman (i.e. the electrician), the number of Pitches, the number of workers executing the task, and the location (construction section and level) is recorded. Predecessor and successor information are visualized with arrows. As explained before, the methodology is based on the MPM approach.

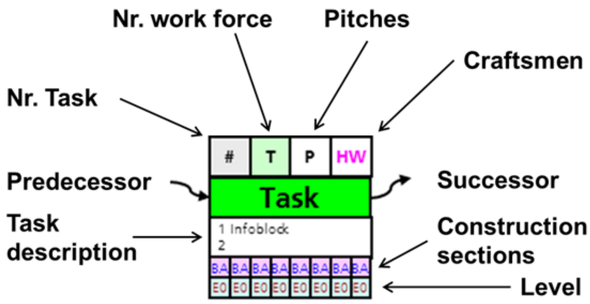

Figure 5. Detailed IBEP-Network Planning Description

Considering the Project scenario 1 - Hotel 3.0 a number of 52 tasks were recorded in the network map (figure 6).

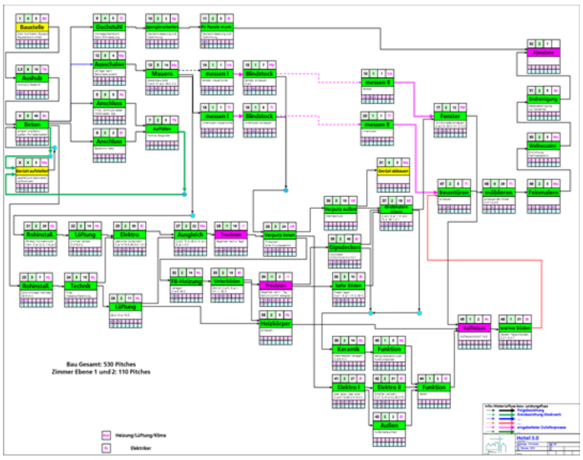

Figure 6. Network Planning – Project 1 Hotel 3.0

As in the EMPM methodology, cycles are taken in consideration (Kerbosch and Shell 1972). For example, scaffolding must be extended before concrete can be poured in the next level. Furthermore embedded supply chains, like the window installation process as described in Dallasega *et al.* (2013) are indicated in the map. Here, steps like taking the measurements of the structural openings by the window manufacturer on site for producing subframes with right dimensions are included in the map. In addition, drying times, like the floor screed drying duration, are emphasized. This means that no craftsman can step onto the pavement on the first day and that 2 to 4 weeks must pass before the floors can be put down.

To standardize and abstract scientific findings, process models were elaborated. A process model in this case refers to a standardized sequence of tasks, which can be adapted to different project scenarios by varying just its parameters. A practical example could be the floor structure. The sequence of activities for different project scenarios (a hotel building, an office building, etc.) might include the basic installation by a hydraulic specialist, the ventilation installation, the basic installation by the electrician, the installation of the compensation layer to protect the pipes, the interior plastering, the under floor heating installation, laying the screed and finally laying the floors.

Step 2: Pitching

The Pitching concept derived from manufacturing was used to synchronize different crafts on site. This allows the introduction of a steady workflow on site. As stated by Rother and Shook (2009), establishing a consistent, or level, production pace creates a predictable construction flow, which by its nature identifies problems and enables quick corrective actions to be taken. Based on Project 1 - Hotel 3.0, a new definition of "1 Pitch" suitable for the construction sector was developed. The consistent increment of work (Pitch) is calculated as follows:

$$1\,Pitch = \frac{\dfrac{Job\,content(8h)}{Craftsmen\,team}}{Construction\,section} \qquad (1)$$

As visualized in equation 1, a standard increment of work specified as 1 Pitch was introduced in the Process Reengineering.

For every task, the respective amount of Pitches was calculated. A practical example could be the laying of carpet floor in Project 1. Every double room consists of 25 square meters of carpet floor and 5 square meters tiled floor (bathroom). According to a flooring expert who joined one project workshop, 1 person could reach around 25 square meters a day. This means that for the task "carpet floors", 1 Pitch for every room was calculated. This means that a job content of 1 day should be calculated for the professional flooring expert (1 Person) in room nr. 1 located in the 2nd basement level. In other words this means that during this Pitch, just the professional flooring expert, works in double room nr. 1. Introducing this rule improves labor efficiency and safety because the different workers do not interfere with each other's tasks. For 12 double rooms in the second basement, 12 Pitches have to be considered. If there are 2 professional flooring experts, 6 Pitches should be calculated.

Step 3: Paced Time Schedule

The Paced Time Schedule consists of a multidimensional view. Considering Project 1 – Hotel 3.0, construction sections are visualized on the y-axis, so called Pitches (Working Days) on the x-axis and the tasks and responsible crafts are visualized internally in the map (figure 8).

During the shell construction phase, the division is done in levels (second basement level, first basement level, ground floor, first floor, roof) and during the interior construction, the division is done within the levels (rooms section, corridor area) as explained in Step 1.1. Of pivotal importance and impact are the long drying times in the shell construction phase, which impede a parallelization of interior constructions (i.e. erecting interior walls). The work load for every craft-team is visualized with bars and includes the quantity of Pitches, the respective Task and the responsible craft-team (figure 7). Furthermore, the bar is referenced with the corresponding task in the Network Planning Map.

Figure 7. Extraction Paced Time Schedule – Hotel 3.0

During the workshops, different priority rules were determined with the participating actors.

1) As one can recognize, in the interior construction phase a gradual planning was performed. The strategy behind this is that craft-teams start in one construction section and move in a flowing way through the whole building. Moreover, efficiency is reached through learning curve effects. A practical example is the laying of the floor screed, where the responsible craftsmen starts in the room-section, proceeds in the corridor area of the second basement level, restarts in the swimming pool section of the first basement level, and so on. So, a steady craft workflow, as visualized in figure 8 can occur during the construction project.
2) The corridor area was considered as the last location where work should be done. It was bypassed because of the drying times.
3) The different tasks/crafts were scheduled from the bottom to the top of the building. This was done to reach a high parallelization degree.
4) The engineering room was chosen as a buffer, which means that crafts were first scheduled in construction sections with a high job quantity, like the room section, and at least in the engineering room for balancing the labor capacity.
5) The construction sections were prioritized according to the job content. This means that tasks and crafts were scheduled first in the rooms section, second in the swimming pool area, third in the wellness area, and so on.

In summary, the Paced Time Schedule of the Project 1 - Hotel 3.0 was established by focusing on the capacity utilization of the involved crafts.

On the other hand, in Project 2 – logistics center 30.0, the focus was on capacity utilization of the construction sections (figure 9). The planning was done for the construction sections, trying to minimize construction stops. Here, the crafts are visualized on the y-axis, the Pitches (Working Days) on the x-axis and the tasks and the construction sections internally in the map.

The one-day Pitch was used because scheduling and controlling with a small time interval helps to recognize earlier if the whole process gets out of control. This allows necessary corrective actions to be carried out in time.

For the construction supplier, scheduling the whole project within a one day degree of detail allows an accurate foresight of work completion. This allows components to be ordered in time, facilitating a JIT delivery from production to construction.

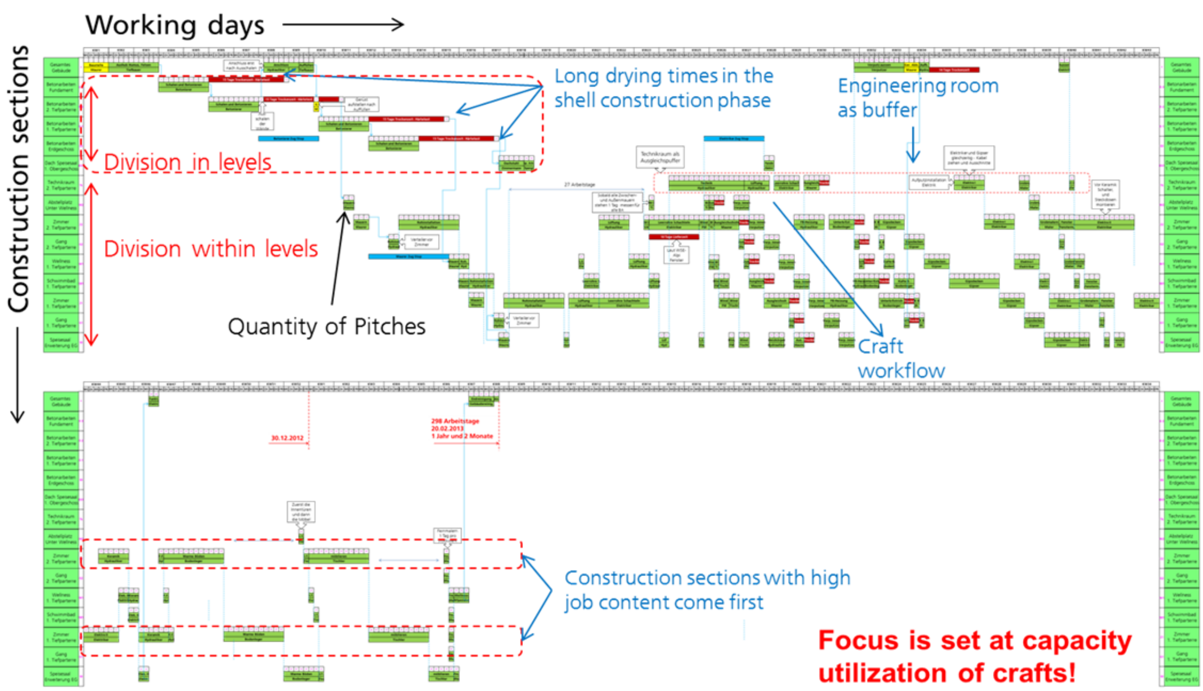

Figure 8. Paced Time Schedule for Project 1 – Hotel 3. 0

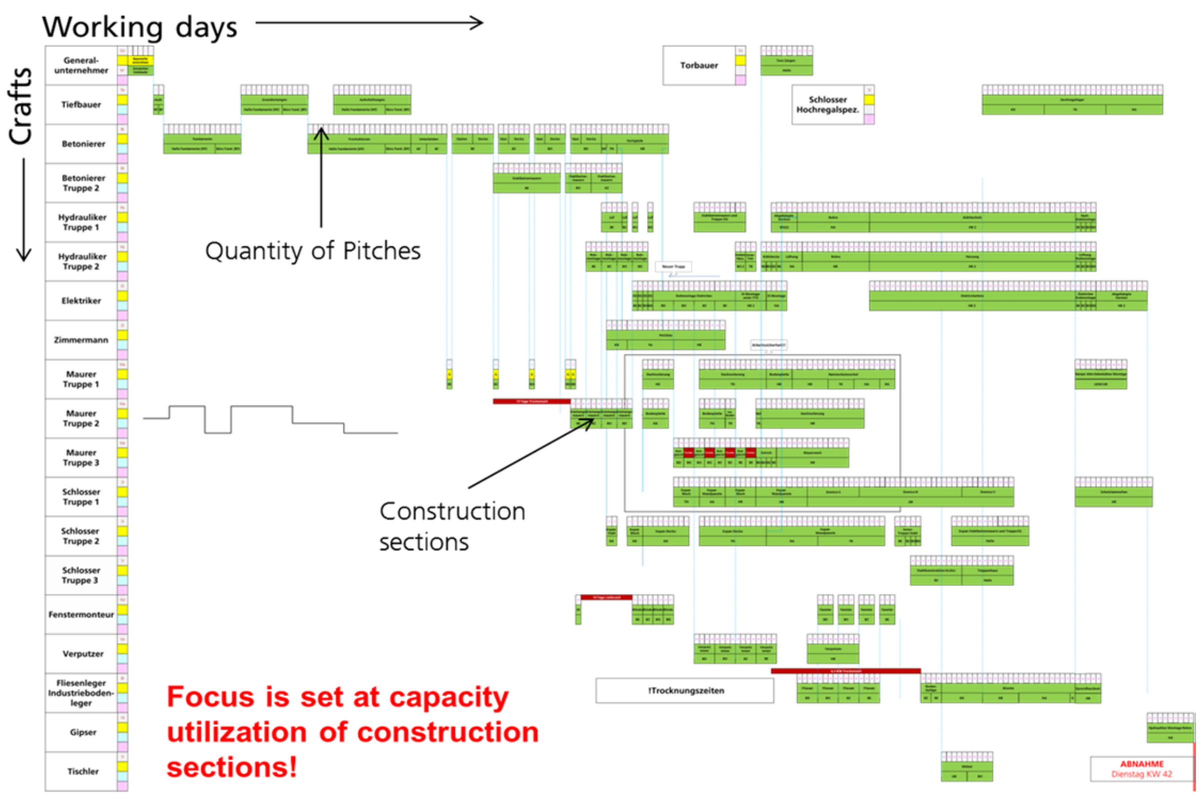

Figure 9. Paced Time Schedule Project 2 – Logistics Center 30.0

Conclusion and Outlook

The paper introduced the new PRECISE production system which focuses on reaching process reliability in construction networks composed of SMEs. The name incorporates the philosophy that detailed planning can limit complexity and unpredictability on site and enable process reliability. In other words, in order to efficiently manage the execution process on site, it has to be planned in an appropriate/detailed way.

One part of the system, the IBEP was simulated within two existing project scenarios. Here the focus of design is switched from product development (building) to process development. Within reengineering, a guideline for reaching process reliability and sustainability was developed.

In on-going research, a real construction prototype will be planned and managed using the design methodology. Based on the PRECISE production system, an appropriate process control approach for small and medium sized projects will be developed.

To allow a JIT delivery of engineered-to-order components, the production (supply) process will be aligned and synchronized with construction on site. For this purpose, a prototype information management system will be developed in the ongoing b4f project.

Based on the prototype system, future research activities will be focused on appropriate Information Technology (IT) realization and implementation.

By designing the building execution process, the topic of “Interdisciplinary Design – Civil Engineering at the Boundary” was targeted, adapting different process planning methods from other industrial fields to construction. The implications for civil design research and education are that process planning methodologies should be integrated in design education, enhancing competencies and transferring know how for an efficient and sustainable construction management.

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Water Sensitive Urban Design: Dhaka City

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Abstract: Water is both a blessing and a blight for Bangladesh, a riverine country that lies on a delta plain formed by the Himalayan rivers and borders the Bay of Bengal. Straddling the Tropic of Cancer, the country is characterized by heavy seasonal rainfall during the monsoon. Flash floods are common all over the country including Dhaka, the capital city. Rapid urbanization of the city has deteriorated the flooding conditions even more. Industrialization, urbanization and expanding populations, on the other hand, have resulted in over-extraction of groundwater which cause the city to face serious water shortages. This paper aims for a water sensitive urban design for Dhaka city which can meet the city's water demand whilst mitigating the water logging. It provides an overview of various storm water infrastructures that include the innovative concept of storm water collection, treatment and re-use plan with successful examples from different cities. The paper then proposes possible strategies along with restoration opportunities within the urban landscape of the city of Dhaka.

Keywords: Blight, Monsoon, Bangladesh, Water Resource Management, Urban Planning.

Introduction

Dhaka is located within the flood plains of fertile rivers and at the foot of the highest mountain range in the world, the Himalayas - which is also the highest precipitation zone in the world. Water features - rivers and rainfall - historically have shaped the civilization, environment, ecology and the economy of this city.

Rivers served as the main source of water for cultivation and the prime routes for commercial transportation. Once becoming the key business routes, they invited the traders from all over the world and urban settlements started along the banks. However, the city had been frequently inundated with the spills from these rivers throughout years. Dhaka's topography is also a huge issue related to flooding as the elevation of the city varies. The low lands act as a temporary detention basin for flood water. During severe inundation a large portion of the city goes under water. Such incidents were experienced in 1954, 1987, 1988, 1998, and 2004. Rainfall, on the other hand, has an enormous effect on the city's water management. Dhaka experiences about 2000 mm of rain annually, 80% of which falls during the monsoon (June-October) (Yahya *et al*. 2010). According to the Bangladesh Water Development Board (BWDB), 448 mm of rainfall was recorded during 24 hours in Dhaka on 27 July, which was the highestrainfall in the history of Dhaka (Sparrso Newsletter 2010). Heavy rainfalls occasionally extend up to several days which may vary from 95-131 days during the monsoon period (Tawhid 2004).

Initial planning of Dhaka city undertook some actions for flood prevention and mitigation. A flood protection embankment was built along the southern front of Dhaka to protect the city from flooding and prevent river erosion. In addition, several canals, wetlands and natural depressions - marshes and swamps - were incorporated in the plan for storm water detention and drainage. These wetlands and natural depressions primarily collected the storm water and then slowly released them to the peripheral rivers through the network of canals. At present, most of these natural retentions are filled by the construction of new structures - buildings, roads, parking and other urban infrastructures - increasing the amount of run-off. Though the city is provided with two separate sewer systems - waste water sewers and storm water sewers - these are not sufficient enough to hold heavy downpours. Paved streets and building rooftops send huge volumes of storm water very quickly into the storm sewer and the system overflows. The city goes under a meter of water after almost every heavy rainfall. The water carries fossil fuels, solid waste, silt, and domestic wastes and ends in the surface water. This contaminated water generates water borne diseases which affect the health of the people. In addition, the city encounters severe consequences from the water logging: damage to infrastructure, destruction of agriculture and aquatic habitats and disruption of traffic movements and individual livelihoods.

A different scenario occurs during the dry season, when people experience an immense shortage in water supply which results from the city's over-dependence on ground water. Dhaka Water Supply and Sewerage Authority (DWASA), which solely provides water for the city, primarily relies on ground water extraction. A small volume of water supply comes from surface water by DWASA's two water treatment plants. According to a DWASA report, more than 80% of the total supply of water comes from ground water source and the rest from surface water. Groundwater extraction has increased over the last few decades resulting in groundwater mining and lowering of the water level. Due to over extraction, the ground water table of the aquifer under Dhaka city is declining 1-3m per year which results in water supply shortages (Rahman and Hossain 2008). Dhaka is facing an estimated water shortage of about 500 million liters per day (Islam *et al.* 2011) and water demand for Dhaka city is expected to reach 3200 mld by 2025 (Rahman and Hossain 2008).

Scope

Urbanization has an enormous impact on natural water systems especially in riverbank cities like Dhaka. The expansion of the urban built environment results in the proliferation of asphalt and concrete and the displacement of agriculture and forestland. Construction of buildings, roads and other infrastructures requires the clearing of large green fields and the filling of natural detention basins. These activities results in substantial increase in impervious areas which in turn increases the amount of polluted runoff that reaches the rivers. As a result, river banks erode, downstream flooding increases, and water becomes polluted which is detrimental to the public health and also the ecosystems that depend on these water bodies. This cataclysm can be turned into beneficial use through the integration of storm water infrastructure in urban design. Storm water management results in profound changes to the urban landscape. Storm water infrastructures are effective in checking storm-water runoff and water logging on the roadway. They also contribute to ground water recharging and the greening of the city. On the other hand, storm water management is considered as a possible answer to the global water use problem especially where storm water is plenteous and the scope for development of groundwater based water supply system is limited or costly. Storm water has huge potential in supplementing the domestic water requirements that can reduce the overdependence on ground water extraction. These outcomes stimulated the research on storm water integrated urban design strategies that are both climate responsive - can reconcile the urban environment with the natural water system - and participatory - engaging professionals, decision makers and local citizens in design decisions.

Places Envisioned for Storm Water Management

The two primary approaches for storm water management are the roof based approach and the land based approach. The roof based approach is associated with building rooftops and temporary or permanent shading roofs. The land based approach deals with retention basins, bio-swales, and permeable pavements. Roof catchments are less expensive to treat as they contain fewer pollutants and they are easy to construct, operate and maintain. They are built and maintained locally and possible for both potable and non-potable usages with minimal treatment. Land catchments are best for ground water recharge as they allow infiltration. They reduce soil erosion and enhance bio diversity but are not suitable for potable usages as they are more likely to be polluted and contaminated by fossil fuels and other waste. Land uses influences the selection of approaches. Land use types that already have vegetation are the most readily convertible and are best suited for land based management. Underutilized buildings and open areas can be restored with roof based storm water management and can be combined with land based management too. Through geographic maps and site visits, this research has envisioned potential places for storm water management within the urban landscape of Dhaka city and inquired into various storm water infrastructures apt for those areas.

Water Bodies

Dhaka city was designed with a large number of water bodies including lakes, canals, wetlands and natural depressions-marshes and swamps. These water bodies played important role in the natural environment of the city. They helped in retaining excess storm runoff and the over flow of rivers. The present scenario shows that many of the water bodies are filled by built structures and the existing water bodies are polluted due to direct runoff. Therefore proper measures are needed for the conservation of the existing water bodies along with storm water management. The polluted storm water runoff can be checked though various physical, chemical and biological processes, utilizing wetland plants.

Bridgeport in Valencia, California is one successful example of storm water management for lakes. The project was designed with water quality filters that collect initial runoff and retain it long enough for the majority of pollutants to be removed. The wetland planter areas filter out waste from runoff utilizing wetland plants.

Figure 1. Bridgeport, California. Source: PACE.

Parks

The glorious history of Dhaka is associated with public parks and playgrounds, many of which occupied large areas with water bodies. They were created to serve the recreational purposes of the city. Many of these parks are nonexistent due to the growing number of built structures and the remaining are in a rundown condition. Redesigning them with slopes, terraces, cascades, porous walkways, bridges and catchment basins, grassy swales alongside park roads, hard courts with porous materials or as the top of water cisterns, rain gardens and planting trees that are capable of absorbing more water will not only bring their life back but also will contribute to mitigating the city's water problem. Forested areas in the parks are good natural infiltration zones. They are good sources for ground water recharge and they can reduce a large amount of storm water runoff.

One of the examples of park storm water management is Atlanta's Historic Fourth Ward Park. The park includes a storm water detention pond that has been designed to increase the sewer capacity, reduce the burden on aging city infrastructures, and minimize downstream flooding and property damage.

Figure 2. Historic Fourth Ward Park, Atlanta. Source: Historic Fourth Ward Park Conservancy

Surface Parking

Surface parking is one of the most neglected features of urban design in Dhaka city. There are several underutilized surface parking lots with impervious paving. The building construction code of metropolitan Dhaka city requires almost every building to have some parking areas but the code does not imply for any sustainable design of these areas to get additional benefits. The design of these areas is often ignored by architects and planners though these parking lots can be used by restoring them with storm management. Vegetated swales, slopes, infiltration basins and green roofs are some prevalent approaches for storm water management. Fossil fuels and other pollutants in the parking areas contaminate the storm water and make it unusable. In such conditions, the best approach is the rain catchment roof that holds the water before contamination. The roof can be temporary and operable and can also be alternatively used as a solar roof. Additional run off from surroundings can be reduced through the design of porous paving on the floor and vegetate swales in the curbsides and edges. They delay the storm water flows by capturing and holding runoff in on-site catch basins and allow the storm water to percolate directly into the soil and recharge the groundwater. The rain catchment roofs along with the pervious paving and vegetate swales can lessen excessive heat exchange.

The Sunset Swales Parking Lot Retrofit project in San Francisco is one example of surface parking storm water management. The parking lot includes two types of storm water management methods: vegetated swales and infiltration basins, which work together to capture and purify the water that drains off the paved parking areas. The vegetated swales were designed to capture storm water runoff from the parking area and pass on in to the small infiltration basins at the low end 'bulb-outs' of each swale.

Figure 3. Sunset Swales, California Source: Conrad (2011)

Medians, Squares and Roundabouts

The major streets of Dhaka city are designed with medians and roundabouts for traffic management. Many of them are provided with either sculptures or plantations for the beautification of the city. In addition to their primary function, if these medians and roundabouts are restored with storm water infrastructures, they can protect the street from flash floods and reduce the amount of runoff.

One of the award winning roundabout storm water management projects is the new roundabout in a busy five-way intersection in Downtown Normal, Illinois. The roundabout has placed an extensive rainwater collection system in an abandoned underground storm sewer where the runoff from the surrounding streets is stored and purified using UV filters and ground filters with vegetation.

Figure 4. Uptown Normal Circle, Illinois
Source: Town of Normal

Sidewalks

Sidewalks are another negligent feature of Dhaka city's street. Many cities around the world have been successful in restoring their sidewalks with porous materials and drainage strainers at some intervals for storm water management. And these sidewalks have attracted more people on the street and made the cities greener and more livable.

The SW 12th Avenue at Portland, the award winning "Green Street Project" from the American Society of Landscape Architects (ASLA), is one of the best examples for sidewalk storm water management. The project has transformed a previously underutilized landscape area between the sidewalk and street curb into a sustainably managed street storm water runoff that captures, slows, cleanses, and infiltrates the street runoff into a series of landscaped storm water planters.

Figure 5. SW 12th Avenue Green Street
Source: The City of Portland, Oregon

Buildings

At present, there are no specific design policies or design guidelines for the practice of storm water management in buildings. Dhaka Rajdhani Unnayan Kartripakkha has developed building construction codes which require the integration of new policies along with storm water management. Current construction codes mandate a percentage of the total site area to have open spaces and specific setbacks in relation to the total site area and building height to allow enough natural light and ventilation. But the codes do not imply any additional use of these spaces. Research had shown that these spaces often remain underutilized. Therefore, new policies can include mandatory storm water management for these open spaces - driveways and surface parking with porous materials; bio swales along the street side that allow some street runoff to prevent water logging; and lawns with rain gardens. Besides, building elevation can consider green terraces and vertical gardens for retaining storm water rather than allowing the water to quickly run to the streets. Roofs can be provided with either storm water harvesting infrastructures or rain gardens. The Institute of Water Modeling (IWM) estimates that if 60 percent of the rain falling on the existing concrete rooftops in Dhaka were harvested, it could provide nearly 200 mld of water to residents each day (Rahman and Hossain 2008). Design practice with storm water management should be promoted with rewards to encourage the designer and house owners. The government should provide incentives for the individual practice of storm water harvesting through partial reimbursement of monthly water usage bills.

The Buckman Heights Apartment Complex in Portland has integrated storm water infrastructures in the courtyard, in the parking lot and in the roof. Runoff from the building roof is piped under the lawn area and the sidewalk to the central courtyard planters. The planters act as infiltration basins allowing storm water to soak into the ground. The parking lot is sloped toward the landscaping. Landscape beds along the front of the building are designed to treat and absorb storm water from a portion of the roof.

Figure 6. Buckman Heights, Portland
Source: Water Environment Research Foundation

Storm Water Management Strategies

Efficient Use of Space with Multiple Programs

Every square inch of land counts for a highly dense city like Dhaka due to its geographic constraints and growing populace. The land-man ratio has made land the most precious resource. The supply of urban land is highly limited and the city cannot afford land for installing additional infrastructures. Therefore, the built environment requires multi-functional plans along with sustainable programs like storm water harvesting, gray water recycling, the installation of solar panels, and so on. Existing large scale projects like educational institutes, administrative buildings, terminals, shopping malls, housing complexes, play grounds, parks and parking are likely to be restored with such programs. Public institutes, administrative buildings and housings constitute a large area of the city which are best suited for storm water management.

Decentralization of Storm Water Management

The decentralization of water management is more manageable and lessens both the water transportation and distribution cost. Therefore storm water catchment and treatment should be managed locally instead of sending the water to a central plant. Small community based storm water harvesting should be practiced in individual residences. The stored storm water can be used in gardens, washrooms, laundries and cooling appliances. This separate distribution for non potable water usages will reduce the pressure on potable water supply and allow less ground water extraction.

Provision of Unpaved Surfaces

Urbanization has provided a little or no scope for the city's ground to breathe. The built environment has hindered the natural water management system by covering a large portion of the city's ground and by ceasing its natural infiltration. Impervious paving has contributed to the increased storm water runoff and heat stress. Unpaved surfaces are not only better for the water management but also for underground life.

Application of Innovative Sustainable Models

The Bangladesh Government is spending a large amount of money for maintaining the existing drainage system and is planning to install more underground drainage pipes to overcome the present water logging in Dhaka city. However, the conventional method alone will not be sufficient to handle the circumstances and raises the need for innovative sustainable applications. New inventive models will not only assist in successful water management but will create public awareness on climate change and the constraints of resources.

Collaboration Among Professionals

Designers, planners, policy makers and other advocates of water sensitive urban development can turn the city's water problem into environmental and community assets. A close coordination among urban authorities and agencies and collaboration between the public and private sectors is needed for the effective management and sustainable operation of urban drainage systems.

Summary

The United Nations 2025 population projection for Dhaka city indicates a large increase in the population density. These gigantic numbers will put enormous pressure on the water consumption and the existing water management system. To alleviate this water scarcity, worsening water shortages and curb drops in groundwater levels, finding an alternative source of water supply for Dhaka city has become a must. Surface water from the surrounding rivers are contaminated by industrial and domestic waste disposal and needs extensive treatment which make it less likely to be used as an alternative source. In such cases, water professionals and water specialists urge the use of storm water as an alternative source of water. On the other hand, experts believe that the impact associated with climate change - increasing sea-level, changing rainfall patterns, and increases in the frequency and intensity of extreme events - will lead to more flooding and drainage congestion in Dhaka city. Storm water sensitive design has a huge potential to alleviate the rainfall induced water logging of Dhaka city. The volume of storm water that is a hazard and a nuisance today can be turned into a resource and a productive public benefit tomorrow with sensitive design decisions.

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An Axiomatic Design Approach to Reconfigurable Transportation Systems Planning and Operations

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Abstract: Transportation systems represent a critical infrastructure upon which communities' and nations' economic and social development depends. As infrastructure systems, they must be planned and operated to efficiently and safely move both people and goods. The needs of passengers and freight are uncertain and continually changing, which represent not only changes in system behavior, but also changes in system architecture. Such changes occur in the planning time scale when the system is intentionally modified, but also in the operational time scale when sudden and oftentimes unexpected changes occur (i.e. a bus or train breakdown). Addressing these changes requires a systematic representation of the evolution of the system architecture. This paper expands on recent work in which a theory of degrees of freedom in manufacturing systems was developed with the use of Axiomatic Design. The theory is specialized to reconfigurable transportation systems, which meet the Axiomatic Design definition of large flexible systems. The methodology is then applied on a small subsection of the Mexico City public transportation network to demonstrate its use in reconfigurability measurement and decision-making at the planning and operations time scales.

Keywords: Axiomatic Design, Reconfigurability, Reconfigurable Transportation Systems, Transportation Itineraries, Transportation Planning and Operations.

Introduction

Transportation systems represent a critical infrastructure upon which communities' and nations' economic and social development depends. In the 1990s, transportation systems the world over became increasingly strained by the continually evolving needs of a growing population that has trended towards concentrating in cities for the past 100 years (de Weck *et al.* 2011). Transportation systems pose particularly troublesome challenges for engineers due to their inherent nature as legacy systems, as well as the economic, political, and social factors that figure prominently in their decision-making – all of which makes them true engineering systems (de Weck *et al.* 2011). A key challenge is the need to find efficient ways to reallocate and/or adjust the capacity and capabilities of these systems to the places and times that need them most. These changes must be implemented quickly (a time scale of minutes) in order to minimize the disruption to supply lines and passenger traffic. Additionally, a transportation system's resilience in the face of unplanned disturbances or events becomes an important quality factor. In order to achieve and support solutions for these issues, it becomes necessary to model the evolution of the system architecture. Reconfigurable transportation systems are proposed as a possible solution (Baca *et al.* 2013; Viswanath *et al.* 2013). They are defined formally as follows:

Definition 1. Reconfigurable Transportation System: A system designed at the outset for rapid changes in structure, in order to quickly adjust capacity and functionality in response to sudden changes in stakeholder requirements (Baca *et al.* 2013).

Reconfigurable transportation systems are those in which new capabilities are added only when needed. These incremental changes require decisions to be made in the planning and operations of transportation systems.

This paper recalls the Axiomatic Design approach called transportation degrees of freedom, developed in Farid (2008), Baca *et al.* (2013), and Viswanath *et al.* (2013). A small case study illustrates the usefulness of this method in the planning and operations phases of transportation engineering. The reason for choosing Axiomatic Design over more established design methodologies is twofold: first, the transportation degrees of freedom are defined in terms of both the function and form of the evolving system architecture; second, it bridges the traditionally graph theoretic approach to the engineering design community.

The remainder of the paper proceeds as follows. The Background section provides the basis for the methodological developments and discussion to follow, with brief introductions to graph theory (van Steen 2010; Newman 2010; Lewis 2009), Axiomatic Design (Suh 2001), and transportation degrees of freedom (Baca *et al.* 2013; Farid 2008). The

Transportation Degrees of Freedom section then recalls previous work on transportation degrees of freedom (Baca *et al.* 2013; Viswanath *et al.* 2013) which is framed in a transportation system context. The Case Study section illustrates the methodological developments on a small subsection of the Mexico City public transportation system. The Planning and Operations in Transportation Systems section describes the reconfigurability applications of these measures in the planning and operations timescales. The Conclusions section summarizes the work and results, and suggests avenues for future work.

Background

This section summarizes the relevant existing literature and provides a foundation for the measures presented and implemented in the next two sections. Some concepts are necessary to proceed with the discussion. These are presented in three steps. The first gives a brief introduction to graph theory. The second introduces Axiomatic Design, with a particular focus on large flexible systems. The third discusses a taxonomy of transportation system degrees of freedom as presented in earlier work.

Graph Theory

Graph theory is an established field of mathematics. It has application in many fields of science and engineering where artifacts are transported between physical locations (van Steen 2010; Newman 2010; Lewis 2009).

Graph theory has found extensive usage in transportation networks. For decades, it has proven useful in providing abstractions of transportation systems for operations research. However, it has limitations from an engineering design and systems engineering perspective. The graph theory definitions focus on the abstract form of the transportation system and not on the transportation functions or how they are realized. Such approaches are likely to have limitations in systems of heterogeneous function and form. Furthermore, "because the system function and its realizing form have been abstracted away, such approaches may not lend themselves to active control solutions that implement reconfigurable transportation system architectures" (Baca *et al.* 2013).

Axiomatic Design

Axiomatic Design is a systems design methodology developed by Dr. Nam Pyo Suh at the Mechanical Engineering Department at MIT in the 1970s. It was first published in 1978 and derives its name from the use of design axioms – laws for which there is no proof, but also no counter-proof - governing the analysis and decision-making process in the design of high quality products or systems.

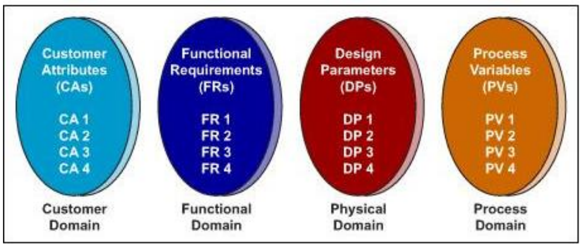

Figure 1. The four domains of Axiomatic Design (adapted from Suh 2001)

There are two fundamental concepts in Axiomatic Design: domains and design axioms. There are four domains – illustrated in Figure 1 - which explicitly describe the design activities that must be followed: first, understand the customer's needs (in the customer domain, in the form of customer attributes or CAs); second, define the problem that must be solved (in the functional domain, in the form of functional requirements or FRs); third, create and select a solution (in the physical domain, in the form of design parameters or DPs); fourth, analyze and optimize the proposed solution (in the process domain, in the form of process variables or PVs). Finally, the resulting design can be checked against the customers' needs, thus completing the design cycle. Decisions in one domain are mapped onto the domain on its right. In other words, for each pair of adjacent domains, the left represents "what we want to achieve" while the right represents "how we propose to achieve it".

The second fundamental concept of Axiomatic Design is the two axioms for which this method is named. They are formally defined as follows:

Definition 2. The Independence Axiom: The independence of functional requirements must always be maintained (Suh 2001).

Definition 3. The Information Axiom: The information content of the design must be minimized.

The Independence Axiom can be reinterpreted as choosing FRs and DPs in such a way that a specific DP can be adjusted to satisfy its corresponding FR without affecting other FRs. The Information Axiom can be reinterpreted as choosing, among those designs that satisfy the Independence Axiom, the one with the maximum probability of success.

The mapping between domains can be represented by a design matrix, which shows the relationship between FRs and DPs, or between DPs and PVs. For the former, the design matrix is commonly known as the knowledge base of the system and is a fundamental part of the measures implemented in this paper.

In contrast to graph theory, Axiomatic Design of large flexible systems provides a natural engineering design description of transportation systems (Baca *et al.* 2013). Suh (2001) defines large flexible systems as systems with many functional requirements that not only evolve over time, but can also be fulfilled by one or more design parameters. In transportation systems, the set of functional requirements is taken as the set of transportation processes, **FR** = {Transportation Processes}. The set of design parameters is taken as the set of transportation resources **DP** = {Transportation Resources}. The definitions of a transportation process and transportation resource are adapted from Farid (2008) where they were used in a production system context.

Definition 4. Transportation Process: A transportation resource-independent process $p_u \in P$ that transports individuals between stations.

Definition 5. Transportation Resource: A vehicle $h \in H$ capable of realizing one or more non-null transportation processes such as a bus or train.

Axiomatic Design has been previously applied in the design of road intersections (Pena *et al.* 2010; Thompson *et al.* 2009a, 2009b; Yi and Thompson 2001), airport terminals (Pastor and Benavides 2011), and shipping companies and ports (Celik *et al*. 2009a, 2009b; Kulak 2005). The work in this paper expands the scope to include the entire transportation system network.

Once the high-level functional requirements and design parameters have been established, they may be simultaneously decomposed to establish full functional and physical hierarchies as part of a rigorous engineering design process. A civil engineering example of such work may be found in Gilbert III *et al.* (2013a, 2013b). While this goal is not the objective of this paper, establishing the measures presented in this paper in terms of the evolving high-level system architecture variables in both function and form grounds the methodology within the engineering design literature.

Mechanical Degrees of Freedom

The concept of degrees of freedom as applied to large flexible systems comes from previous work in the field of automated reconfigurable manufacturing systems (Farid 2007, 2008) where an analogy was drawn between mechanical and production degrees of freedom. The analogy is redrawn in Baca *et al.* (2013) and Viswanath *et al.* (2013) for transportation systems, and is recalled in this subsection.

At its most basic level, a mechanical system is defined by links and coordinates (Shabana 1998). Links make up the physical composition of the mechanical system; coordinates are used to express the evolution in time of a continuous state which results in motion. The physical form of transportation systems takes the form of transportation resources. Regarding the time evolution of transportation systems, an event-driven evolution of discrete states is more appropriate for the system architecture analyzed in this paper (Cassandras and Lafortune 1999).

The degrees of freedom of a multi-body mechanical system come from its links (physical composition) and coordinates (possible dimensions of a change of state). It is calculated as the number of links times dimensions minus any applicable constraints (Shabana 1998). Analogously, the degrees of freedom of transportation systems will come from the combination of feasible transportation processes and their associated resources minus any applicable constraints (Baca *et al.* 2013).

Mechanical degrees of freedom are classified as either scleronomic, i.e. time-independent, or rheonomic, i.e. time-dependent (Shabana 1998). For event-driven systems' degrees of freedom, they will be scleronomic or rheonomic in relation to their sequence dependence (Baca *et al.* 2013).

Transportation Degrees of Freedom

This section recalls previous work on transportation degrees of freedom (Baca *et al*. 2013; Viswanath *et al.* 2013; Farid 2008) which arises from the Axiomatic Design knowledge base for large flexible systems. First, the transportation system is defined to provide a clear problem definition. Next, the measure of scleronomic transportation degrees of freedom is presented as a quantitative indicator of the sequence-independent capabilities of the transportation system. Then, the rheonomic transportation degrees of freedom measure is included to address sequence-dependent system capabilities. Finally, the passenger degrees of freedom measure is recounted.

Problem Definition

A transportation system is composed of a set of transportation processes $P = \{p_1, \ldots p_{\sigma(P)}\}$ that transport passengers from an arbitrary station b_{y1} to b_{y2}, where the σ() gives the size of a set. If B is taken as the set of stations, then by definition there are $\sigma^2(B)$ such processes. Of these, $\sigma(B)$ are "null" processes where no motion occurs (i.e. going from station 1 to station 1).

These transportation processes are realized by a set of resources $R = \{r_1,\ldots,r_{\sigma(R)}\}$. An event $\varepsilon_{uv} \in E$ (in the discrete event system sense) (Cassandras and Lafortune, 1999) can be defined for each feasible combination of transportation process p_u being realized by resource r_v.

The transportation system knowledge base describes the transportation system's capabilities and is defined formally as follows:

Definition 6. Transportation System Knowledge Base: A binary matrix J_S, of size $\sigma(P) \times \sigma(R)$, is defined, where element $J_S(u,v) \in \{0,1\}$ is equal to one when event e_{uv} exists (Baca *et al.* 2013).

Interestingly, the Axiomatic Design knowledge base itself forms a bipartite graph (van Steen 2010) between the set of processes (e.g. functional requirements) and resources (e.g. design parameters).

Scleronomic Transportation Degrees of Freedom

The scleronomic transportation degrees of freedom, developed by Baca *et al.* (2013), Viswanath *et al.* (2013), and Farid (2008), are defined formally as follows:

Definition 7. Scleronomic Transportation Degrees of Freedom (Farid 2007, 2008): The set of independent transportation events E_S that completely defines the available transportation processes in a transportation system. Their number is given by:

$$DOF_S = \sigma(E_S) = \sum_{u}^{\sigma(P)} \sum_{v}^{\sigma(R)} \left[J_S \ominus K_S \right](u,v) \quad (1)$$

where Ks is the scleronomic constraints matrix of size $\sigma(P) \times \sigma(R)$ whose elements $K_S(u,v) \in \{0,1\}$ are equal to one when a constraint eliminates event e_{uv} from the event set. Such constraints can arise from any phenomenon that reduces the capabilities of the transportation system, such as vehicle breakdowns, line closures, or road detours. The $\ominus$ operator is equivalent to Boolean subtraction or A·not(B). Equation 1 can be rewritten in matrix form (Abadir and Magnus 2005):

$$DOF_S = \langle J_S, \bar{K}_S \rangle_F = tr(J_S^T \bar{K}_S) \quad (2)$$

The scleronomic transportation degrees of freedom measure allows the usage of the Axiomatic Design knowledge base for further detailed engineering design (Baca *et al.* 2013). Furthermore, the constraints matrix captures the potential for operational and planning constraints. As a result, it provides a flexible expression of the transportation system architecture and its capabilities in the planning and operational phases.

Rheonomic Transportation Degrees of Freedom

The previous subsection recalled the independent transportation degrees of freedom measure. However, a transportation system is inherently constrained by sequence-dependency. Rheonomic transportation degrees of freedom, also developed by Baca *et al.* (2013), Viswanath *et al.* (2013), and Farid (2008), are formally defined as follows:

Definition 8. Rheonomic Transportation Degrees of Freedom (Farid 2007, 2008): The set of independent transportation strings Z that completely describes the transportation system language. Their number is given by:

$$DOF_\rho = \sum_{u_1}^{\sigma(P)} \sum_{u_2}^{\sigma(P)} \sum_{v_1}^{\sigma(R)} \sum_{v_2}^{\sigma(R)} \Big[[J_S \cdot \bar{K}_S](u_1,v_1) \cdot [J_S \cdot \bar{K}_S](u_2,v_2) \cdot \bar{C}_\rho(u_1,u_2) \Big] \quad (3)$$

where C_ρ is

$$C_\rho(u_1,u_2) = \begin{cases} 0 & \text{if } \bmod((u_1-1),\sigma(B)) = (u_2-1)/\sigma(B) \\ 1 & \text{otherwise} \end{cases} \quad (4)$$

Further matrix-based simplifications of this measure may be found in Baca *et al.* (2013), Viswanath *et al.* (2013), and Farid (2013). Note that this definition considers two transportation degrees of freedom in a sequence. Mathematically speaking, for one degree of freedom to follow another, the destination of the former must be equivalent to the origin of the latter. Intuitively speaking, certain transportation events may follow one another, while other combinations are not possible. The rheonomic transportation degrees of freedom provide a sequence-dependent measure of the capabilities of the transportation system.

Passenger Degrees of Freedom

The passenger degrees of freedom measure was developed from the scleronomic and rheonomic transportation degrees of freedom. It measures the number of ways that a passenger in the transportation system may be transported from a desired origin to a final destination (Baca *et al.* 2013). It is defined formally as follows:

Definition 9. Passenger Degrees of Freedom (DOF_p): The number of passenger itinerary strings in the language L_ρ between a desired origin y_1 and a desired destination y_n (Baca *et al.* 2013). Their number is given by:

$$DOF_p = \sum_{i}^{n} DOF_{pi} \quad (5)$$

where it is equal to the sum of itineraries consisting of 1 leg, 2 legs, up to the number of n legs deemed practical by the passenger. The number of one leg routes uses the scleronomic degrees of freedom measure in Eq. 1, while the number of two-leg routes uses the rheonomic transportation degrees of freedom found in Eq. 3. In both cases, the scleronomic constraint matrices must be updated to incorporate both the desired origin y_1 and the desired destination y_n. The same logic used to derive Eq. 3 from Eq. 1 follows for 3-leg and up to n-leg journeys. The scleronomic constraint matrices would have to be similarly updated. For the number of n-leg routes –i.e. the number of n-event rheonomic transportation degrees of freedom, $DOF_{\rho n}$

$$= \sum_{u_1,\ldots,u_n}^{\sigma(P)} \sum_{v_1,\ldots,v_n}^{\sigma(R)} \left[\prod_{x}^{n-1} [\mathrm{J}_s \cdot \bar{\mathrm{K}}_s](\mathrm{u}_x, \mathrm{v}_x) \cdot \bar{C}_\rho(u_x, u_{x+1}) \right] \cdot [\mathrm{J}_s \cdot \bar{\mathrm{K}}_s](\mathrm{u}_n, \mathrm{v}_n) \quad (6)$$

The calculation of this formula may be greatly facilitated using the graph theoretic methods provided in Baca *et al.* (2013), Viswanath *et al.* (2013), and Farid (2013).

This section recalled the methodological developments presented in Baca *et al.* (2013) and Viswanath *et al.* (2013). The scleronomic and rheonomic transportation degrees of freedom were used to model passengers in terms of transportation sequences. The final measure, passenger degrees of freedom, allows for the enumeration of passenger itineraries. All three measures exhibited the same common elements also found in mechanical degrees of freedom: discrete events captured in Axiomatic Design knowledge bases, constraint matrices, and a Boolean difference of these two matrices.

Case Study: Mexico City Public Transportation System

Baca *et al.* (2013) and Viswanath *et al.* (2013) used a subsection of the Mexico City Public Transportation System to demonstrate the passenger itinerary enumeration made possible by the passenger degree of freedom measure. This same system is once again used to illustrate the usefulness of the methodological developments of this paper – this time, the planning and operations applications of the passenger degree of freedom measure.

For purely illustrative purposes, the system boundary is narrowed down to a few square blocks around the City Center (Zocalo area), which is considered to be the exact geographic center and hub of activity in the city. This reduces the system from over 300 stations to a much more manageable 9 stations within the system boundary. A smaller example provides a better understanding of the relevant principles without any loss of generality or extensibility to systems of larger size (Baca *et al.* 2013).

The knowledge base for the defined system is an 81x2 binary matrix, J_S. The rows represent the possible transportation processes between stations (9 stations, 9^2=81 FRs), including same-station FRs. The columns represent the transportation resources (in this case, the two transportation modes: Metro and Metrobus). By definition, the transportation process is equal to 1 if there exists at least one resource capable of realizing it within the given window of time. The time scale is adjusted throughout depending on the application and the desired measurement, which is another advantage of using an Axiomatic Design-based approach.

Number of Passenger Itineraries

The scleronomic and rheonomic (2-leg) transportation degrees of freedom for this given system were found to be 56 and 422, respectively, within a 1-hour timescale. In other words, 56 out of the 81 transportation processes were achievable with a 1-leg journey (including same-station FRs). This high number can be explained by the small area of the example. Also, 422 itineraries of 1 and 2-leg journeys were possible between the 9 stations (again, including same-station FRs) – journeys of 3 legs or longer are ignored, under the assumption that passengers would consider them no longer practical within such a small geographic area.

The number of passenger itineraries, while a powerful quantitative measure of the capabilities of the system, is only one of many system measures that can be derived from the transportation degrees of freedom. The next section provides a discussion of some of these applications.

Planning and Operations in Transportation Systems

Axiomatic Design has proven to be a powerful tool for developing transportation degrees of freedom as a measure of reconfiguration potential. This section discusses four classes of applications for these developments: redundancy and flexibility, reconfigurable operations, reconfigurable planning, and reconfigurability valuation.

Redundancy and Flexibility

The terms ‘redundancy’ and ‘flexibility’ are ubiquitous in the engineering design field. Flexibility is a valued property in systems and one of the major “ilities” in systems engineering (de Weck *et al.* 2011). Redundancy, on the other hand, is often maligned by designers and engineers alike. Redundancy in the physical composition of a system is undesirable as it adds costs and complexity, but does nothing to improve system functionality. While this is true of most systems, transportation systems require some measure of redundancy. Redundancy is a critical component of resilience, which itself reflects the uncertain nature of transportation systems. How much redundancy is required by transportation systems makes for an interesting research topic to be sure, but is not the focus of this paper.

The Axiomatic Design knowledge base provides a measure of redundancy and flexibility. The sum of the non-zero elements in each column of the knowledge base serves as a measure of flexibility of the given transportation resource. The sum of the non-zero elements in each row provides a measure of redundancy for the given transportation process (Farid 2008).

In the case study, redundancy becomes evident by the fact that the Metro and Metrobus share many stations. If the system were expanded to include all 300+ stations in the public transportation network, it would illustrate this claim even more strongly: most of the shared Metro/Metrobus stations are located at a high density near or around the City Center, which has the highest volume of passengers. This redundancy pays dividends on a regular operational viewpoint by providing alternatives to passengers and much-needed relief for the most congested lines and times. In the event of an unplanned failure, redundancy is necessary to ensure that the most important routes are still being realized by the available transportation resources. Furthermore, redundancy enables another life cycle property, namely resilience. In unforeseen natural disasters such as hurricanes and floods, redundancy allows for rapid evacuation and enhanced emergency services.

Redundancy may take different physical forms. There are many public transportation systems around the world that build parallel tracks for their subway lines, which allows them to run more than one train at a time. Others, meanwhile, build different lines that run along the same route for long distances. The Tokyo subway is a good example of the former; the New York City subway, of the latter. The transportation degree of freedom approach allows the representation of both cases, since there is a remarkable amount of freedom in how the functional requirements and design parameters are represented in the knowledge base. For the case study, the DPs were defined as transportation modes. Individual tracks, road lanes, trams, and/or buses could have been used instead to give a more granular view. Additionally, the timescale can also be adjusted to a minute-by-minute scale for real-time operation or on a daily scale for a more temporally coarse measure of transportation capabilities.

Reconfigurable Operations

The scleronomic transportation degree of freedom provides a quantitative measure of the system capabilities and how they can be changed. The rheonomic transportation degree of freedom provides a quantitative measure of how system capabilities can be combined into sequences. In both cases, these measures describe the impact of these reconfigurations on the system capabilities.

The concept of transportation degrees of freedom can be applied to achieve reconfigurable system operations (Baca *et al.* 2013) when the knowledge base and constraint matrices are used over a short and regular time interval - i.e. one hour - a reconfiguration process can be said to occur from one hour to the next. One such example is bus and metro lines that are not operational throughout the entire day; their period of non-operation can be captured in the constraints matrix. Unplanned disturbances and breakdowns can also be captured at the operational timescale.

There are many types of constraints that can limit the reconfiguration potential of the transportation system. Fixed schedules are an example of inflexible operations. Buses and trains leave at a fixed time from a fixed location, regardless of existing traffic conditions or irregularities elsewhere in the system.

Real-time operational control decisions are making their way into transportation systems in what are often called Intelligent Transportation Systems (Chowdhury and Sadek 2003). Active real-time switching in railways can be viewed as making real-time reconfigurations and may be aided by the Axiomatic Design knowledge base of the system. The Tokyo Metropolitan Traffic Control Center optimizes traffic flow in the city, making use of more than 15,000 vehicle detectors and 300 traffic information boards to regulate the flow of car traffic, pedestrian traffic, and public transportation. Real-time transportation scheduling algorithms are another key enabling technology for reconfigurable operations, and many of them use matrix-based mathematical programming methods similar to the transportation degree of freedom approach.

Reconfigurable Planning

The concept of transportation degrees of freedom can also be applied to medium and long-term planning decisions. In the medium-term, the schedules generated by system operators represent a planning activity in which transportation resources are allocated to achieve the transportation resources in the most efficient manner. In the Axiomatic Design language, this is akin to mapping design parameters (transportation resources) to the functional requirements of the system (transportation processes). In the long-term, planning decisions may include semi-permanently modifying the system's capabilities by adding or removing modes of transport, lines, or individual transportation resources (such as buses or trains). These changes to the transportation network are reflected in changes to the knowledge base, which can be expanded to include new transportation processes (i.e. rows in the knowledge base) and new transportation resources (i.e. columns in the knowledge base).

Returning to the Mexico City case study, Baca *et al.* (2013) showed how the flexibility and reconfigurability of the system increased dramatically with the introduction of the Metrobus in 2005. This was done by computing the passenger degree of freedom measure both before and after 2005. Many other measures of quality –passenger capacity, transit times, and greenhouse gas emissions, among others- are possible and addressed in the next subsection.

Premium on Reconfigurability

The concept of transportation degrees of freedom as a measure of reconfiguration potential draws questions about the value of this reconfigurability. To this end, it is important to recognize that each transportation degree of freedom can be associated with quantifiable measures of cost, benefit, as well as return on investment.

In the operational domain, each degree of freedom can be associated with a passenger capacity, passenger traffic, operating cost, and revenue. Alternatively, it can be associated with energy consumption, transit time, greenhouse gas emissions, and externalities (Baca *et al.* 2013). Returning to the case study, it is possible to adjust the capacity of the system by adding trains or buses. Employing this approach, these decisions can now be automated and conducted in a systematic fashion that facilitates deeper engineering design of automation and control systems.

In the planning phase, similar measures can be associated with each degree of freedom to determine the impacts of changing the system. The required investment to make the degree of freedom possible - and potential additional revenue earned from it - can aid in the long-term decision-making process. Similarly, such an approach can be used to model future energy consumption, greenhouse gas emissions, and transit times from a technical planning perspective. In the case of the Mexico City Public Transportation System, these planning calculations can be done after the fact to reveal interesting results. The passenger capacity, for instance, was calculated to increase by 35% in the defined subsystem with the introduction of the first Metrobus line in 2005. The greenhouse gas emissions were calculated to increase by 48% due to Metrobus buses being more energy efficient and running on dedicated surface streets (and, hence, not being stuck in traffic). The capacity growth figure matches the statistics provided by the Mexico City Transportation Authority in 2006 (35%), while the emissions reduction figure falls short by a small margin, 48% vs. 40% (Metro 2013).

This section has shown that it is possible to value reconfigurability as an operations stage life cycle property. Furthermore, it provides a measure of the long-term reconfiguration process in the planning phase, which can be valued in terms of time or monetary cost (Farid 2007).

Conclusions and Future Work

This paper has expanded on the planning and operations applications of the transportation degrees of freedom first developed in Baca *et al.* (2013). The work rests firmly on the foundation of previous work on production degrees of freedom (Farid 2007, 2008), which was contextualized to transportation processes and resources. The application-neutral Axiomatic Design model of a knowledge base of functional requirements and design parameters explicitly represents the transportation system - with its associated processes and resources - and its constraints in matrix form.

The transportation degree of freedom measures come in two varieties. The scleronomic degrees of freedom assess available transportation processes irrespective of sequence. The rheonomic degrees of freedom consider path dependency. These measures and their applications were discussed practically, extending the Mexico City case study from Baca *et al.* (2013). These measures showed how the reconfiguration potential of the Mexico City public transportation network changed in the face of additional resources. It also represented potential reconfigurations in which stations were added, modified, or removed. These measures also show that many insights into the system structure can be gained if the allocation of processes is considered in relation to resources. In this way, they provide a thorough understanding of the potential for reconfiguration in large flexible systems - such as transportation networks.

From a theoretical perspective, the Axiomatic Design models have multiple advantages (Baca *et al.* 2013). From a modeling point of view, these models avoid any unnecessary information and can be decomposed and incorporated into design processes specifically aimed at achieving system resilience and reconfigurability (Baca *et al.* 2013). In an intuitive way, each element corresponds to a physical relationship that is fundamental to the desired reconfiguration. Furthermore, active control solutions can be developed that utilize the knowledge base and constraint matrices in the operational timescale.

In future work, the authors seek to develop reconfiguration “ease” measures (Farid 2007, 2008), which is the other half of the reconfigurability measurement question. Measurements of other key characteristics of systems, such as integrability and convertibility, also provide a challenging avenue of future work (Farid 2007). Finally, all these measures would benefit from their application in industrial case studies.

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An Axiomatic Design Based Approach to Civil Engineering

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Abstract: Civil engineering projects are becoming increasingly intricate and interdisciplinary with a growing need to answer a number of complex socio-economic and environmental issues during the design process. Because each project is unique, civil engineers rarely develop formal techniques to ensure that customer requirements are properly captured and that the complex set of trade-offs affecting a building are fully understood. Understanding issues early in the design process is important, as this is when the designer is able to have the largest impact on the final product. In this paper Axiomatic Design and Product Platform Design are proposed as methods to address this issue. A case study of the design of a temporary housing shelter is presented to demonstrate how both methodologies can be applied to a complex civil engineering project that includes a number of socio-economic and environmental constraints.

Keywords: Temporary Housing, Civil Engineering, Axiomatic Design, Modularity, Large Flexible Systems

Introduction

There is a growing trend in the civil engineering community to embrace new design methodologies to handle mounting project complexity. Today, a civil engineer needs to consider life-cycle issues such as constructability, durability, life-cycle maintenance, energy efficiency, environmental impact and social-economic impact in addition to traditional concerns such as structural integrity and initial cost (Albano and Suh 1992). “The increasing complexity of architectural design entails the need for a more rational and systematic approach to the design process, especially in the conceptual design phase when decisions with fundamental and extensive effects on appearance, performance and cost are made” (Marchesi *et al.* 2013). In fact, there is a clear need to find a way to identify faulty design decisions as early in the design process as possible. Civil engineering work typically starts with a broad conceptual design performed by an experienced civil engineer. Generally the engineer uses his/her past experiences to develop the conceptual design that is then brought into a detailed design phase. However, “[r]igorous analytical methods and optimization schemes are used for decisions that impact project cost plus or minus 7% (detailed design phase), while decisions that impact project costs plus or minus 30% (conceptual design phase) are internalized” (Albano and Suh 1992).

Although past experience plays an important role in design, the growing complexity of design problems makes it nearly impossible for all but the most gifted engineers to adequately capture all of the problems in the conceptual design phase. This problem is further compounded as customer demands become more diverse and segmented and more stakeholders have a role in the creation of the project.

Since traditional civil engineering design methodologies are not adapted to assist in the design of the conceptual phase of a project, engineers are beginning to look into other engineering fields for a solution. As is noted by Marchesi *et al.* (2013), “[t]he design of architectural systems has to be optimized with respect to a large number of different (sometimes conflicting) requirements and constraints, and the solution has to be selected from different available alternatives.” It is the contention of this paper that Axiomatic Design (AD) and Product Platform Design will improve the conceptual design of complex civil engineering projects, ultimately resulting in a more appropriate and less expensive solution.

The remainder of the paper will proceed as follows. Section 2 introduces the concept of AD. Section 3 discusses another design methodology called Product Platform Design that works well in complement with AD. Section 4 presents a case study where AD and Product Platform Design are applied to the conceptual design of a temporary housing unit. Section 5 concludes the paper and introduces ideas for future work.

Axiomatic Approach to Design

Axiomatic Design (AD) is proposed as a methodology to develop a new approach for the conceptual design of complex civil engineering projects. AD is a well-established methodology from mechanical engineering design that is quickly moving into other design oriented engineering fields. Section 2.1 briefly introduces the fundamental axioms that govern Axiomatic Design, while section 2.2 delves into the Axiomatic Design approach for larger flexible systems. For more detailed information regarding Axiomatic Design, the reader should refer to Suh (2001) or Suh (1995). For examples of the application of AD to other Architecture, Civil or Transportation Engineering projects, see Marchesi *et al.* (2013), Albano and Suh (1992) or Baca and Farid (2013) respectively.

Fundamental Concept of Axiomatic Design

The heart of Axiomatic Design is the axioms upon which it is built. An axiom is a "truth that cannot be derived but for which there are no counterexamples or exceptions" (Suh 2001). There are two axioms that make up Axiomatic Design. They are known as the independence axiom and information axiom. These are formally stated by Suh (2001) in the following manner:

Axiom 1: The Independence Axiom. Maintain the independence of the functional requirements.

Axiom2: The Information Axiom. Minimize the information content of the design.

Both of these axioms will be discussed in further depth in the following section. However, in order to better understand these axioms, the reader should first understand the concepts of domains and the mathematics that support each axiom.

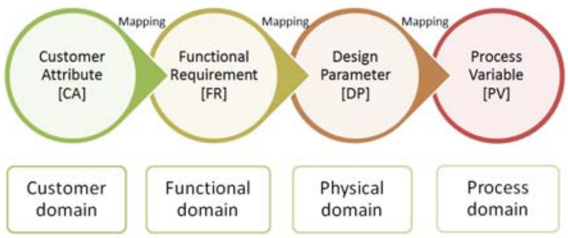

Figure 1. Domains of Axiomatic Design (Suh 2001)

According to Suh (2001), there are four domains that make up the world of design: the customer domain, the functional domain, the physical domain and the process domain. Domain relationships are shown in figure 1 above. As can be seen in the figure, each domain has a direct effect on the domain to its right. This is a graphical way of displaying the concept that the domain on the left is "what" the designer wants to achieve, and the domain on the right is "how" this will be achieved.

The customer domain is where the customer attributes (CAs), or needs, are defined. CAs are characterized by the attributes that the stakeholders are looking for in the product, process or system. For instance, the CAs for a building may include *keep space safe from intruders*, or *create an area large enough to provide living space for five people*.

The second domain is called the functional domain. This is where the customer needs are defined in terms of functional requirements (FRs), constraints (Cs) and non-functional requirements (nFRs). FRs are defined as the minimum number of independent requirements that entirely illustrate a design goal, and represent the objective and intent of the designer (Suh 2001, Thompson 2013). Cs set a hard limit on specific qualities, and nFRs describe characteristics of the final product or system, often in terms of aesthetics or durability. Thompson (2013) provides an in depth breakdown of the different elements of the functional domain. *Maintain shape*, *prevent erosion*, and *manage expectations* are possible FRs. Examples of constraints include *cost*, *weight*, and *density*. Lastly, nFRs include descriptions such as *durable*, *easy to use*, or *aesthetically pleasing*.

The third domain is called the physical domain and is the home of the design parameters (DPs) that were devised to fulfill the FRs within the specified Cs. Examples of DPs are *rebar reinforced concrete walls* or *double paned glass*.

The last and final domain is the process domain. It is in the process domain that the process variable (PV) used to achieve a specified DP is identified. This could include using *wooden forms to create concrete pillars* or *steel rollers to form a W section*.

One of the most important elements of Axiomatic Design is the mapping of properties from one domain to the next. Though mapping occurs from one domain to the next as in figure 1, another important process that occurs in Axiomatic Design is *the zigzag*. The zigzag process between the FRs and DPs is shown in figure 2**Error! Reference source not found.**. Though a similar zigzag process happens between the DPs and PVs, the primary focus is generally on the interaction between the FRs and DPs. The zigzag process works by first specifying a high-level FR. This is mapped onto the physical domain to create a high-level DP. The high-level DP is used to decompose the high-level FR into lower level FRs. The lower level design decision must remain consistent with the higher level design decisions. The FR should be defined without thinking about an already existing design solution. This is important because it allows the designer to be creative throughout the design process and possibly allows for the creation of innovative design solutions.

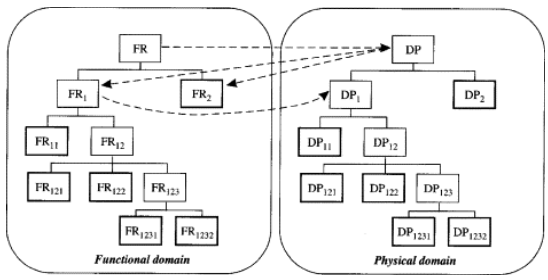

Figure 2. Zigzagging between FRs and DPs (Suh 2001)

Though figure 2 above shows the visual domain hierarchy, it can also be represented mathematically using matrices. If the generalized vector form of the functional requirements and the design parameters are represented by {FR} and {DP} respectively, then the matrix relationship can be expressed using the following equation (Suh 2001):

$$\{FR\} = [A]\{DP\} \tag{1}$$

In this equation, [A] is the design matrix that shows the relationship between the functional requirements and the design parameters, and it also determines whether or not the proposed design violates the independence axiom. The resulting design matrix can be either uncoupled (equation 2), decoupled (equation 3), or coupled (equation 4), where a zero in the design matrix represents low or no correlation between the FR and DP.

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X_{11} & 0 \\ 0 & X_{22} \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \tag{2}$$

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X_{11} & 0 \\ X_{21} & X_{22} \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \tag{3}$$

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \tag{4}$$

An ideal design will be an uncoupled design (equation 2). An uncoupled design means that FR1 is fulfilled by DP1, and FR2 by DP2. Changing DP1 will have no effect on FR2, and vice versa. This means the system is extremely flexible to changes made to the FR. This is in direct contrast to the coupled design (equation 4). As Albano and Suh (1992) explain, "the physical significance of a coupled design is the fact that the resultant solution is not flexible to change. The design has poor adaptability because it is difficult or impossible to adjust for any variations in the requirements due to loading change, interferences with other engineering disciplines, construction change orders, and varying environmental conditions."

The remaining design notation or decoupled design (equation 3) is also an acceptable form of design that, like the uncoupled design, does not violate the independence axiom.

The second axiom, the information axiom, provides a numerical way to compare different designs and ultimately select the best design by minimizing the information content. The information content is a way of describing the probability of success of achieving the FRs with the selected DPs. It is defined by

$$I = \log_2(1/p) \tag{5}$$

where p is the probability of success. However, the information axiom plays a minor role in this paper. For additional information regarding the information axiom, the reader should refer to either the Axiomatic Approach to Structural Design (Albano and Suh 1992), or Axiomatic Design: Advances and Applications (Suh 2001).

Large Flexible Systems

Axiomatic Design has developed a way to design systems whose set of functional requirements evolve over the use phase of the system's life cycle. Suh describes a system that needs to be able to "reconfigure itself to satisfy a different subset of FRs throughout its life" as a "large flexible system" (Suh 2001). The structure of a knowledge base for a large flexible system is modeled as in equation 6 below.

$$\begin{gathered} FR_1 \$ (DP_1^a, DP_1^b, ..., DP_1^r) \\ FR_2 \$ (DP_2^a, DP_2^b, ..., DP_2^r) \\ \vdots \\ FR_m \$ (DP_m^a, DP_m^b, ..., DP_m^r) \end{gathered} \tag{6}$$

Equation 6 states that any number of DPs can satisfy the specified FR. The addition of a DP to this equation is similar to expanding the database. As the database grows, the design can become more dynamic. For example, the DP of a "concrete column," "steel column," or "wooden column" can meet the FR of "support a vertical load". As technology continues to evolve, should a new DP be created to "support a vertical load" this DP will be added to the database of DPs. The database will expand as new technologies are developed, and in doing so help ensure the best possible design can be achieved (Gilbert III *et al.* 2013, Suh 2001). The built database can be applied to a system that has FRs whose subsets vary as a function of time. Equation 7 below is an example of such a subset.

$$\begin{aligned} @t = 0 &\rightarrow \{FR\}_0 = \{FR_1, FR_4, FR_5\} \\ @t = T_1 &\rightarrow \{FR\}_1 = \{FR_2, FR_3, FR_5\} \\ @t = T_2 &\rightarrow \{FR\}_2 = \{FR_3, FR_4, FR_6\} \end{aligned} \tag{7}$$

In this example, the FRs at time zero are FR_1, FR_4, and FR_5. To satisfy each of these FRs, a corresponding DP from a knowledge base, like the one in equation 6, will need to be found for each FR. However, it is important to ensure that the independence axiom is not violated. In other words,

DP_1 must affect only FR_1 and have no effect on FR_4 and FR_5. The next part of equation 7 states that at time T_1 the FRs of the system change and a new set of DPs will need to be found (Suh 1995). Functions that remain constant, such as FR_5, should continue to work with the DPs selected for the new FRs. Using this method to model the design of a large system is useful when the system must be reconfigurable on demand. It is particularly helpful when the designers know at the start of the design process that customer needs are going to change over time. As will be demonstrated in the case study later in the paper, the reconfigurability of a large flexible system is an advantage when designing temporary housing.

Product Platform Approach to Design

In civil engineering nearly every problem is unique, encompassing a different set of requirements and stakeholders. Traditionally, it is uncommon for civil engineers to systematically seek economies of scale in a set of engineering projects.

Close analysis of many large-scale engineering projects, such as the temporary housing example provided in the case study, reveals that it is not uncommon to have a core set of functional requirements that are identical across multiple components of a project. When this occurs, civil engineering designers tend to use an informal system to take advantage of the commonalities. Though civil engineers do not often use a formal platform, there are methodologies from other disciplines that are applicable to this type of situation. Product Platform Design is a design concept that is well suited to helping to achieve a variable set of functional requirements, while at the same time capturing the economic advantages of economy of scale.

Product Platform Design is a recently developed approach to product architecture that shares a number of similarities to AD, and if used concurrently with AD theory, can help to significantly improve the design of modular systems (Gilbert III *et al.* 2013). A modular system is an approach to a problem that subdivides functionalities into smaller parts (modules) that are created separately but can then be used in conjunction to drive multiple functionalities.

The central idea of Product Platform Design is the concept of using a common platform to create a number of different products. “This approach allows manufacturing cost to be reduced by capturing economies of scale in the production process, and helps decrease the design cost as only a few aspects of each module need to be designed uniquely” (Gilbert III *et al.* 2013). The competitive advantage made possible by Product Platform Design is dubbed “mass customization” since it gives businesses the ability to meet a number of unique customers’ needs at a low cost (Simpson 2004, Simpson, *et al.* 2005).

Critics of modular design often note the potential to “over-design” modules that have lower demands. Scale-based product families are a potential solution to overcome this constraint as well as an effective way to improve the flexibility of Product Platform Design. “Scale-based product families are developed by scaling one or more variables to “stretch” or “shrink” the platform and create products whose performance varies accordingly to satisfy a variety of market niches” (Simpson 2004).

A popular example of this concept in literature is the Honda automobile frame platform. The Honda platform can be “stretched” in length and width to satisfy the length and width requirements of any car frame design (Simpson 2004).

While this methodology is not often applied in civil engineering, the growing field of modular construction regularly utilizes methodologies similar to Product Platform Design in the design of structures (Lawson *et al.* 2012). Lawson claims that among the many advantages of modular construction is the ability to achieve:

- Economies of scale
- Faster speed of construction
- High level of quality control
- Minimum disruption to in situ area
- Adaptability for future extensions

Case Study: Axiomatic Design of a Dynamic Flexible Temporary Housing Unit

In this section, the use of Axiomatic Design and Product Platform Design is illustrated in the design of a generic temporary house. A brief introduction into temporary housing will first be provided in Section 4.1. Section 4.2 establishes the customer requirements that will be used in Section 4.3 to show the benefit of using a large flexible system in the design of temporary housing. Section 4.4 gives an example of an Axiomatic Design decomposition, and Section 4.5 concludes the case study by discussing how the Product Platform Design methodology can be applied.

Introduction

Every year, either because of some form of natural disaster or forced displacement, millions of people are left homeless. After these events, different organizations come together to work with the destroyed community to help restore a sense of normalcy and assist in community rebuilding. It is not uncommon for the slogan of these projects to be “build back better,” though the literature shows that this is rarely the case. Temporary housing that is constructed to help the community’s transition into a semblance of normality when permanent reconstruction is underway is often inadequate and is consistently unable to realize appropriately the stakeholder's needs and requirements (Johnson 2007a, 2007b).

Starting in the 1970's, a typical response to the need for temporary housing was prefabricated units. These units came in a variety of designs and styles, and were built to be shipped as turnkey units to locations affected by a natural disaster or conflict. However, these units suffered from a wide range of problems. "These shelters usually implied standardization and resulted in repetition of a "universal unit" that rarely responded to the specifics of climate, topography, local customs, and local forms of living" (Lizarralde *et al.* 2010). Johnson (2007b) elaborated on how these housing solutions also faced excessively high cost, late delivery, poor location, improper unit designs and other inherent issues.

Another problem that is gaining prominence is how providers of temporary housing "rarely anticipate and plan for a natural transition to permanent housing," nor do they have a plan for how to deal with the units when they are no longer needed (Lizarralde *et al.* 2010). Arslan wrote two papers centered on this problem, and a number of authors discuss it in their analysis (Arslan 2007, Arslan and Cosgun 2008). Units are used for years after their intended lifespan, either taking up space on valuable land, or morphing into a "shantytown."

In addition, temporary housing units can be extremely small and overcrowded. Typical unit sizes range from 15-35m^2, and occupant rates can be as high as ten people per unit (Johnson 2007a). What is notable is that "agencies tend to consider that a fair distribution of resources implies giving the same product to each beneficiary (instead of a more sensitive approach to fair distribution resulted from giving each beneficiary what he/she really needs)" (Lizarralde *et al.* 2010). This results in families of eight people being placed in the same size unit as a family of three. Families who previously ran a business out of their home (a common practice in developing countries) are left with no space for their business. Therefore, the "return to normalcy" the temporary housing unit was supposed to signify is a complete farce for them. The result is families' adding to their units ad hoc, often resulting in structures that will become a safety liability in the event of a subsequent disaster.

Unfortunately, the problems of the past are still present today, as temporary housing units are often culturally or climatically inappropriate, have large delays in their design and construction, and ultimately cause health and social problems within temporary housing camps (Johnson 2007a, 2007b). Some units are so inappropriate that the intended residents never use them and they remain empty, a useless financial drain on the entire rebuilding process.

Customer Requirements

The customer requirements for a temporary structure are not always clear or easy to define. However, in any project it is imperative to spend time to understand the customer requirements for the structure. In this paper, the customer requirements for the temporary house were determined based on typical requirements for a structure. These were determined from mistakes made in early temporary housing projects in literature and are shown in table 1 (Arnold 2009).

Though all of the requirements in table 1 are important in the design, many will become either constraints or nFRs and will not appear in the design decomposition.

Use of Large Flexible System

A large number of the problems experienced by existing temporary housing can be alleviated by approaching the problem as a large flexible system. There is a universal set of requirements that nearly every person wants in a house. These requirements remain the same if the house is for a single person or for a family of eight, if it is built in Southeast Asia or Northern Ireland, or even if it is for a fisherman or a home business owner. These core requirements remain the same even if the person living in the house situation changes. In addition, just like a permanent house, temporary housing should be able to change and adapt to the change in requirements. Therefore, the question becomes how to meet the core requirements of a temporary house while still allowing the structure to be highly customizable.

The proposed solution is a modular housing unit centered on a "core" module that can be combined with other modules to accommodate the user's fluctuating requirements. The FRs and DPs of the "core" and each module unit are designed with an AD knowledge base that includes the possible additions (though additional modules would be easy to add to the knowledge base as needed). The literature agrees with this approach arguing that the "need for the housing to be temporary motivates a flexible approach to the building's set of functional requirements" (Gilbert III *et al.* 2013, Simpson *et al.* 2005)

Figure 3 demonstrates a conceptual knowledge base that serves as a framework for the design of a modular temporary house. The modularity of the structure allows diverse user requirements to be achieved with separate module units, where the "studio module" is the "core" unit. As discussed in the introduction, the nature of temporary housing suggests the need for flexibility. One module may need to address multiple FRs. This can be seen by summing each column. The redundancy of how the functional requirements are realized is another important aspect as it allows for specialization. This is seen by summing the rows (Farid 2008).

Table 1. Customer Requirements for Temporary Structures (Arnold 2009)

Structural:	Support own weight and transfer lateral loads to building frame.
Water:	Resist water penetration.
Air:	Resist excessive air infiltration.
Condensation:	Resist condensation on interior surfaces under service conditions.
Movement:	Accommodate differential movement (caused by moisture, seasonal or diurnal temperature variations, and structural movement).
Sound:	Attenuate sound transmission.
Fire safety:	Provide rated resistance to heat and smoke.
Security:	Protect occupants from outside threats.
Maintainability:	Allow access to components for maintenance, restoration and replacement.
Constructability:	Provide adequate clearances, alignments and sequencing to allow integration of many components during construction using available components and attainable workmanship.
Durability:	Provide functional and aesthetic characteristics for a long time.
Extensibility:	Allow additions.
Reconfigurability:	Allow for adjustment based on occupants needs.
Reusability:	Provide an alternative use of whole structure of individual components when planned use is expired.
Aesthetics:	Do all of the above and look attractive.
Economy:	Do all of the above inexpensively.

The addition of modules not only allows additional functions to be achieved, it also allows for specialization, as mentioned above. An excellent example is a computer and a computer speaker. While most computers today have built in speakers, they are only able to provide basic sound quality. For higher performance computer audio, users need to purchase separate speakers (Gilbert III *et al.* 2013).

The advantages of an AD knowledge base approach to temporary housing can be made clear in an example. Following a natural disaster, a family of two are provided with a "core" temporary housing unit with hopes of moving into permanent housing within six months. However, the reconstruction takes longer than originally planned, and they have a child. The family is in need of additional space. However, instead of adding an informal and possible unstable addition to the house, the family simply adds an additional bedroom module.

Functional Requirement	Design Parameter									
	Studio Module	Bathroom Module	Kitchen Module	Bedroom Module	Living Room Module	Dining Room Module	Study	Hall	Storage (Closet)	Stairs
Support Food Preparation	X		X							
Support Elimination of Human Waste		X								
Support Social Activity	X				X					
Support Relaxation	X			X						
Support Eating	X					X				
Support Personal Hygiene	X	X	X							
Support Sleeping	X			X	X					
Support Work	X					X	X			
Support Exercise	X						X			
Support Connectivity of Rooms	X							X		X
Support Storage	X								X	

Figure 3. Graphical Form of Axiomatic Design Knowledge Base (Gilbert III *et al.* 2013)

Decomposition of Studio Module

The Axiomatic Design method of mapping FRs to DPs by zigzagging provides an excellent method of designing the modules of the temporary house. "This analytical process complements the creative process of synthesizing a design solution and uses the design axioms as objective criteria for recognizing good design decisions" (Albano and Suh 1992). For space, only the studio module will be decomposed in this paper. However, the additional modules can be created by adopting the design of the studio module.

At the highest level, the structure is bound by a single functional requirement, FR0, "Provide 'Platform' Unit that Meets Basic Housing Needs" and can be achieved using the design parameter, DP0, Studio "Core" Module.

Based on the constraints and requirements of a temporary structure above, the second level functional requirements were selected as follows:

FR1= Passively protect and maintain internal climate
FR2= Actively maintain internal environment
FR3= Connect with environment
FR4= Remain structurally sound
FR5= Support user activities

The Design parameters selected to fulfill each of these FRs were:

DP1= Building Envelope
DP2= HVAC system
DP3= Connections
DP4= Structure
DP5= System configuration

Many of the DPs selected at high levels share similar names with the FRs they are fulfilling. This is common, and should be expected particularly at the first level of decomposition.

Table 2 shows the continued decomposition of the zigzag AD process to the second level. The DPs were selected to preserve the independence axiom, which figure 4 demonstrates was well done. Figure 4 is called the design matrix (DM) of Axiomatic Design, and is a visual way of presenting the decomposition of the FRs and DPs. It also can quickly show designers where DPs affect FRs, and clearly shows if the relationship between the FRs and DPs is uncoupled, decoupled or coupled.

As can be seen in table 2 and figure 4, FR1, which passively protects and maintains the internal climate, includes the ability to protect occupants from natural issues such as water, and other problems like intruders and fire. The DPs selected to fulfill these requirements were all related to the envelope of the building.

FR2 actively maintains the internal climate, and uses a number of mechanical functions to keep the internal climate at the appropriate temperature with adequate healthy air. The AD approach to the design allows these systems to change based on the requirements. Here, a fan is used for cooling, however, in a hotter climate this may be replaced with a solar powered AC unit.

FR3, connect with the environment, is decomposed to connect with other modules, allow controllable interaction with the external environment, and connect to infrastructure. These selections were made to allow a further decomposition of each FR without compromising the independence axiom, while also enabling an easier design of a standard platform. Figure 4 shows these were all further decomposed, but for brevity were excluded from the table. The interfaces between each module are key. Without them, the design of the entire concept falls apart. This makes it clear that the design must be simple to connect and include ways to allow the exchange of electricity, water, and people (Gilbert III *et al.* 2013). Design to connect with the external environment is often overlooked except for the most basic function of entering and exiting the building. However, in developing countries, internal and external areas don't have the same degree of separation of western houses. In fact, it is extremely important that the indoor and outdoor areas are closely tied together.

FR4, remain structurally sound, is decomposed to include remain stable, and maintain shape. The DPs chosen to meet these FRs were the foundation and frame. While these are important components of all buildings, they have a few distinctive features unique to temporary housing. For example, they "must be able to maintain their shape despite numerous dynamic loads, including normal loads such as seismic and wind loads, but also will need to withstand forces placed on the frame during transport" (Gilbert III *et al.* 2013). Likewise, since the structure is temporary, the foundation should be designed to be removable at the end of the structure's use to minimize site damage and the resultant loss of value to the property.

Table 2. Second Level Decomposition of Design

FR0*	Provide "Platform" Unit that Meets Basic Housing Needs	DP0*	"Studio Module"
FR0*	Provide "Bathroom" Unit that Provides for Hygiene Needs	DP0*	"Bathroom Module"
FR0*	Provide "Kitchen" Unit that Supports Food Preparation	DP0*	"Kitchen Module"
FR0*	Provide "Bedroom" Unit that Supports Privacy and Sleeping	DP0*	"Bedroom Module"
FR1	Passively Protect and Maintain Internal Climate	DP1	Building Envelope
FR1.1	Keep Out Moisture	DP1.1	Waterproof Shell
FR1.2	Resist Thermal Transfer Through Radiation, Convection and Conduction.	DP1.2	Insulation
FR1.3	Keep Internal Area Dry	DP1.3	Drainage
FR1.4	Protect from Insects	DP1.4	Screen
FR1.5	Protect Occupants from Outside Threats	DP1.5	Locks
FR1.6	Protect from Fire and Smoke	DP 1.6	Fire Board
FR2	Actively Maintain Internal Climate	DP2	HVAC System
FR2.1	Heat Interior Area	DP2.1	Electric Heating Unit
FR2.2	Cool Interior Area	DP2.2	Fans
FR2.3	Maintain Adequate Air Quality	DP2.3	Ventilation System
FR3	Connect with Environment	DP3	Connections
FR3.1	Connect with Other Modules	DP3.1	Standard Interface
FR3.2	Allow Controllable Interaction with External Environment	DP3.2	Controllable Inlet/Outlet
FR3.3	Connect to Infrastructure	DP3.3	Connection Modulus
FR4	Remain Structurally Sound	DP4	Structure
FR4.1	Remain Stable	DP4.1	Foundation
FR4.2	Maintain Shape	DP4.2	Frame
FR5	Support User Activities	DP5	System Configuration

Lastly, FR5, support user activities, is met by DP4, system configuration. This refers to the layout of the internal area of each module. It is in this area that the specific functionality of each unit will be

		DP0 "Studio Module"	DP1 Building Envelope	DP1.1 Waterproof Shell	DP1.2 Insulation	DP1.3 Drainage	DP1.4 Screen	DP1.5 Locks	DP 1.6 Fire Board	DP2 HVAC System	DP2.1 Electric Heating Unit	DP2.2 Fans	DP2.3 Ventilation System	DP3 Connections	DP3.1 Standard Interface	DP3.1.1 Large Portal	DP3.1.2 Inter-modular Electrical Connection	DP3.1.3 Fresh Water Piping Connection	DP3.1.4 Waste Water Piping Connection	DP3.2 Controllable Inlet/outlet	DP3.2.1 Door	DP3.2.2 Window	DP3.3 Connection Modulus	DP3.3.1 Connection to Power Source	DP3.3.2 Connection to Water Source	DP3.3.3 Connection to Waste Water Disposal	DP4 Structure	DP4.1 Foundation	DP4.1.1 Compacted Soil	DP4.1.2 Temporary Foundation Piles	DP4.2 Frame	DP4.2.1 Lateral Bracing	DP4.2.2 Semi-Rigid Frame	DP4.2.3 Columns	DP5 System Configuration
FR0	Provide "Platform" Unit that Meets Basic Housing Needs	O																																	
FR1	Passively Protect and Maintain Internal Climate		X																																
FR1.1	Keep Out Moisture			X																															
FR1.2	Resist Thermal Transfer			X	X																														
FR1.3	Keep Internal Area Dry					X																													
FR1.4	Protect From Insects			X			X																												
FR1.5	Protect Occupants from Outside Threats			X				X																											
FR1.6	Protect From Fire and Smoke			X					X																										
FR2	Actively Maintain Internal Climate									X											X	X													
FR2.1	Heat Interior Area										X																								
FR2.2	Cool Interior Area											X																							
FR2.3	Maintain Adequate Air Quality										X		X								X	X													
FR3	Connect With Environment		X			X								X																					
FR3.1	Connect with Other Modules														X																				
FR3.1.1	Provide Ingress for Users Between Modules															X																			
FR3.1.2	Provide Electrical Connection Between Modules																X																		
FR3.1.3	Provide Freshwater Connection Between Modules																	X																	
FR3.1.4	Provide Wastewater Connection Between Modules																		X																
FR3.2	Allow Controllable Interaction with External Environment		X																	X															
FR3.2.1	Allow Ingress Into and Out of Structure for People																				X														
FR3.2.2	Allow Entrance of Natural Light																				X	X													
FR3.3	Connect to Infrastructure		X			X																	X												
FR3.3.1	Provide Electricity																							X											
FR3.3.2	Provide Running Water																								X										
FR3.3.3	Dispose of Waste Water		X			X																				X									
FR4	Remain Structurally Sound																										X								
FR4.1	Remain Stable																											X							
FR4.1.1	Protect from Erosion																												X						
FR4.1.2	Protect from Differential Settlement																													X					
FR4.2	Maintain Shape																														X				
FR4.2.1	Protect from Lateral Loads																															X			
FR4.2.2	Protect from Dynamic Loads (Wind/ Seismic)																												X	X		X	X		
FR4.2.3	Protect from Vertical Loads																															X		X	
FR5	Support User Activities													X									X	X	X		X				X		X		X

Figure 4. Design Matrix of a Temporary House

achieved. For example, the studio module may include a counter area to help with the preparation of food, or a bathroom that will include a toilet and sink. This was not further decomposed in this paper, as the functionality will depend entirely on individual characteristics of the location for the structure.

Application of Product Platform Design

Product Platform Design is a powerful way to create highly customizable modules to form a house while simultaneously minimizing manufacturing and design costs. In the proposed example, the studio module needs to be a larger module to meet the diverse set of functional requirements with minimal coupling (Gilbert III *et al.* 2013). The kitchen and bedroom need to fulfill fewer functions, so the modules need not be as large. Likewise, the bathroom and hallway module can be smaller still. It is advantageous to conserve space when possible, as it will save the cost of material and land. Keeping the modules appropriately sized for the required functionality is highly advantageous. To achieve the diversity of size but still take advantage of Product Platform Design all modules can be designed and built on a scale-based product family. The scale-based approach "enables the units to continue to capture the benefits of Product Platform Design of having low design and manufacturing cost while achieving high customization" (Gilbert III *et al.* 2013).

Table 2 demonstrates the first two levels of decomposition of a module. The only difference between the conceptual model FRs for the studio module and the other modules is the size and the need to connect to the infrastructure (FR 3.3). When the decomposition is continued to the third and fourth levels, more differences become apparent, but these differences can be handled by not including them in the platform. Further specialization can be added at a later point.

Conclusion

In this paper, the fundamental concepts of Axiomatic Design and Product Platform Design were introduced as potential formal methods for the conceptual design of civil engineering projects. These two theories were applied to a case study of the design of a temporary house to demonstrate their application. The case study showed the advantages of treating the problem as a large-flexible system. It also demonstrated how to use Axiomatic Design in the design process to create improved designs. Applying Product Platform Design theory in addition to AD aided in creating better-defined product functional features. Most importantly, it enabled a new and a unique temporary house design that satisfies customer needs. One additional advantage of using Axiomatic Design is the flexibility it provides. For example, if electricity is not available, it is easy to see that neither a fan nor heating unit will work in the unit. This means the designers need to select another DP that does not require the use of electricity to meet the functional requirements *Heat Internal Area* and *Cool Internal Area*. However, more work still needs to be done to use AD and Product Platform Design in civil engineering.

One place of particular interest for future research is in using the information axiom to help select the best materials for structures like temporary housing. It would also be interesting to test the effects of the conceptual design by completing the design process and creating a physical temporary housing structure.

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Axiomatic Design in Participated Urban Planning: Potentials and Criticism

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Abstract: The Agenda 21 program first suggested in 1992 and the European Directives 42/2001 and 35/2003 later mandated that territory planning in local administrations across Europe must include a participatory decision making process that involves stakeholders in the decision making phase. This decision is supported by the urban sciences and many tools, mainly derived from group facilitation and conflict solving strategies, have been developed and introduced for this purpose. However, the transition from the common top-down to the more effective bottom-up planning approach requires an active involvement of relevant stakeholders, who first need to be sensitized. Fraunhofer IEC has been developing a platform to systematically structure and facilitate the participated process. On the basis of the Metaplan, the European Awareness Scenario Workshop (EASW) and Planning for Real tools, this participated platform foresees an iterative process that efficiently involves different types of stakeholders in order to provide sustainable development scenarios for territory planning. In this framework, Axiomatic Design could become a powerful instrument to validate whether development scenarios fulfill all stakeholders' needs and to determine the most efficient way to implement them. This paper offers possible solutions for the integration of the Axiomatic Design methodology in a participated decision making process for urban development and highlights the potentials, criticisms and possible adaptation strategies.

Keywords: Urban Planning, Participated Urban Planning, Axiomatic Design, Complex Systems.

Introduction

Urban environments represent one of the most complex systems of modern society (figure 1). Cities must meet the needs of stakeholders who have changing, competing and conflicting interests while adapting to changes in culture, technology and the environment. The challenge of the Smart City of the future is to manage this complex mosaic of development by meeting the needs of a rapidly evolving society while remaining sensitive to contextual inputs.

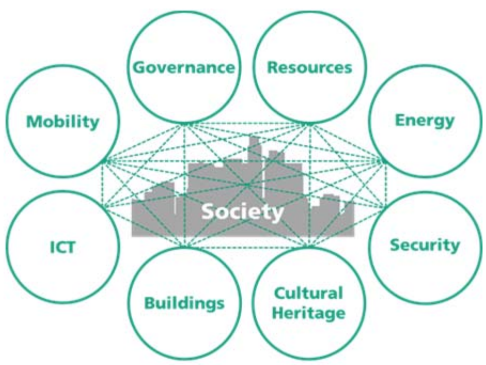

Figure 1. Main Aspects of Urban Environments

By approving the Directives 42/2001 and 35/2003, the European community officially mandated participated planning as a key methodology for territory development across member nations. However, a lean governance strategy is not easy when all the stakeholders have to be involved in the decision making process.

So far, several tools (mainly derived from group facilitation and conflict solving strategies) have been introduced in order to involve all the stakeholders into the participated planning process. Nevertheless, evidences from Italian case studies show that these tools have been used only for the refurbishment of green spaces or for the development of new areas not liable to a conflict of interests. For this reason, it is possible to assert that a real management of urban development has not been faced yet due to strong constraints (intended use of the area already defined) or a lack of interest on the part of the stakeholders.

What if stakeholders will be included in the decision making process without strong constraints?

Could an Axiomatic Design approach improve the efficiency of participated planning tools?

The paper tries to answer to these questions by analyzing existing tools and identifying a strategy to integrate the Axiomatic Design framework into a participated planning process. In a first step the most applied tools are deeply investigated highlighting potential and criticisms. Afterwards Axiomatic Design approach is introduced. Finally, a different approach is proposed by mixing standard tools and Axiomatic Design framework.

Participated Planning Tools

Design and planning activities strongly influence the overall quality of urban life and ensure a higher value for investments in the constructions sector as shown by successful urban design case studies (Urban Task Force 1999; Construction Task Force 1998). Furthermore these activities generate long-lasting impacts on the social, economic and environmental background. This results in a great responsibility for planners and designers who must meet the needs of complex and variable systems like modern society.

Due to this complexity, management (especially in the Italian context) has traditionally relied upon a top-down structure in which a group of technicians was in charge of providing urban instruments to plan the development of settlements (Italian Urban Law n.1150, 1942). These standard instruments have to be published for thirty days and observations or changes to the proposals may be submitted by the community. The lack of competences between the technicians and the community usually does not allow a real constructive dialogue between the two actors to take place during the final revision phase. For this reason, community members feel excluded from the decision making process and the technicians are not able to read community’s needs correctly. Too often this situation generated deep social conflicts. It has also rarely resulted in violent demonstrations.

In order to avoid social conflicts, the European Union strongly pushed toward a different and participated approach especially for urban, infrastructural and territory planning (European Directive 42 2001; European Directive 35 2003). The main objective of the participated approach is to involve the whole community from the beginning. In this way it is possible to collect ideas and identify possible problems before investing time and money in planning activities which have to maintain the standard process. In order to reduce the overall effort of the participated phase, urban sciences codified a series of standard tools.

Participated planning tools may be considered design tools. The most applied ones are: Metaplan, the European Awareness Scenario workshop (EASW), and Planning for Real.

Metaplan

Metaplan is mainly a facilitation methodology to include a group of people in innovation or problem solving. In an early first stage, it uses cards to collect proposals from the participants who also have to cluster and prioritize them. In a second phase, problems are thoroughly investigated and possible solutions are provided identifying a schedule and a responsible person for each solution (Schnelle 1979).

European Awareness Scenario Workshop

In an EASW workshop, participants meet each other in order to exchange experiences and develop a shared vision on the future of their community. The main objectives of the session are: to identify how problems could be solved, if these are more related to specific fields like technology or organization, and who is the stakeholder responsible for providing the solution. In a first stage, participants are divided into 4 independent groups (by stakeholder category) and each one of these groups has to imagine a possible future scenario for their community taking into consideration related problems and solutions. The whole process is based on predefined scenarios, which include different combinations of applied technologies and social organization models. Afterwards, participants have to vote and in detail define the more significant vision. In a second phase, on the basis of the selected vision, ideas have to be collected in order to define a strategy to transfer the vision’s content into the current community structure. Finally, participants are invited to identify the main responsible subject among stakeholders (Fleximodo 1998).

Planning for Real

Planning for Real involves professionals (architects, engineers, planners, sociologist, etc.) in the role of facilitators and coordinators, and communities in the role of players. In an early first stage, a scale model of the area has to be provided to the players in order to collect proposals and suggestions from them. Afterwards, the proposals and suggestion are subdivided and prioritized through a public discussion. In a second phase, the professionals’ team adopts this information as inputs for the technical plan of the area (Gibson 1998).

Axiomatic Design Approach

The Axiomatic Design (AD) approach, which was developed in the 1970s at the Massachusetts Institute of Technology, provides a rational and systematic framework to help designers during the development of products, systems and processes. It allows the solution of design problems by simple axioms and corollaries (Suh 1990). AD may be applied in many different fields which foresee design activities, as several case studies demonstrated.

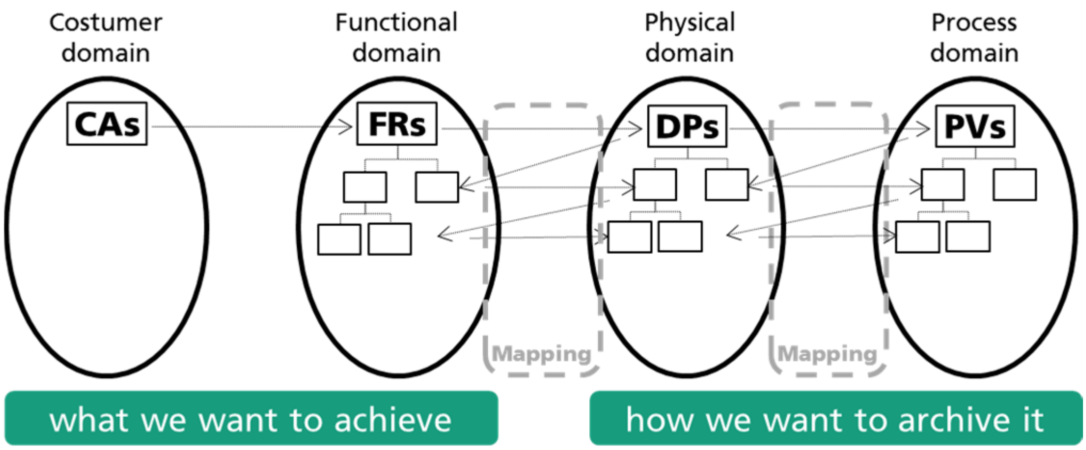

Figure 2. The Design Domains

In the AD framework, a good design has to respect the principles that are codified through two axioms. By definition, axioms are fundamental truths which cannot be demonstrated. They are always valid and contradictions or exceptions cannot be provided. Axioms drive designers towards a synthesis and a selection of a good idea from an infinite number of possible solutions (Suh 1990).

According to Suh, a good design should satisfy the two axioms and has to identify a solution that fulfills the perceived needs through a mapping process. The mapping process foresees an interlinking across all levels between "what we want to achieve", defined through functional requirements (FRs) in the functional domain and "how we want to archive it", defined through design parameters (DPs) in the physical domain. In every field, each design parameter has to fulfill a functional requirement by applying specific knowledge and practices, but always by linking "what we want to achieve" and "how we want to archive it".

The design process begins with the identification of "what we want to achieve" in accordance to predefined customer attributes (CAs) which provide a minimum set of FRs and constraints. Later on, the DPs that fulfill the provided FRs must be defined (Suh 1990).

Constraints define the limits of the design process and they cannot be considered as a FR. Suh (1990) identifies two types of constraints:

- Input constraints - which are constraints in design specification; and
- System constraints - which are constraints imposed by the system in which the design solution must function.

AD foresees a process which is composed by design domains and vertical hierarchies. According to Suh (2001), it is possible identify four different design activities which correspond to four different domains (figure 2):

- The customer domain that includes customer attributes (CAs) or customer needs;
- The functional domain that includes functional requirements (FRs), "what we want to achieve";
- The physical domain that includes design parameters (DPs), "how we want to archive it";
- The process domain that includes process variables (PVs) strictly related with the process needed to transfer DPs into a real product.

AD drives the designer through the different domains by mapping CAs, FRs, DPs and PVs. By definition, mapping is the process of getting from one domain to the other one. Once the CAs are defined, a minimum set of independent FRs and a set of constraints must be provided respecting the main design goals. Afterwards, designers have to fix DPs that satisfy the predefined FRs and, lastly, PVs that plan the product production. Inside each domain, elements should be decomposed into a hierarchy until the design is sufficiently detailed (Suh 2001).

The mapping process may be expressed as a vector relationship:

$$\{FR\} = [A]\{DP\} \qquad (1)$$

where $[A]$ is the design matrix; $\{FR\}$ is the functional requirements vector; and $\{DP\}$ is the design parameters vector. The design matrix results as follows (Suh 2001):

$$[A] = \begin{bmatrix} A_{1,1} & A_{1,2} & \dots & A_{1,n} \\ A_{2,1} & A_{2,2} & \dots & A_{2,n} \\ \dots & \dots & \dots & \dots \\ A_{m,1} & A_{m,2} & \dots & A_{m,n} \end{bmatrix} \qquad (2)$$

where the single element may assume a value equal to 1 whether it is possible identify a relationship between an $\{FR\}$ element and the corresponding $\{DP\}$ element, a value equal to 0 whether no relationship exists.

Design quality has to be evaluated following two main axioms (Suh 1990):

- Axiom 1 – The Independence Axiom: maintain the independence of FRs;
- Axiom 2 – The Information Axiom: minimize the information content of the design.

The Independence Axiom allows the design quality to be assessed. The Information Axiom may be used to select a good idea between different possibilities. According to Axiom 1, it is possible identify three possible configurations of the design matrix as previous defined:

- whether each DP satisfies only one FR, The Independence Axiom is fully respected and the design may be defined as an Uncoupled Design. The design matrix is diagonal:

$$[A] = \begin{bmatrix} 1 & 0 & ... & 0 \\ 0 & 1 & ... & 0 \\ ... & ... & ... & ... \\ 0 & 0 & ... & 1 \end{bmatrix} \qquad (3)$$

- whether the FRs' independence can be obtained only by a special order of DPs, The Independence Axiom is partially respected and the design may be defined as a Decoupled Design. The design matrix is triangular:

$$[A] = \begin{bmatrix} 1 & 0 & ... & 0 \\ 1 & 1 & ... & 0 \\ ... & ... & ... & ... \\ 1 & 1 & ... & 1 \end{bmatrix} \qquad (4)$$

- whether some DPs satisfy more than one FR and it is not possible identify a Decoupled Design, the Independence Axiom is violated and the design may be defined as a Coupled Design. In these cases, no special structure of the design matrix exists.

According to Suh, an Uncoupled Design represents the best design solution (but is rare). A Decoupled Design is acceptable. When a Coupled Design results, designers have to re-start the process once again, until the Independence Axiom is satisfied (Suh 1990).

Comparison Between Participated Planning Tools and Axiomatic Design

Participated planning tools may be defined as design tools. Referring to Axiomatic Design approach, they try to identify (at different levels) constraints, CAs, FRs, DPs, and PVs by demanding the active participation of the final stakeholders in the design process. Through this, it is possible to include their needs automatically in order to avoid a complex market analysis. However, these tools cannot completely handle a complex design process. For example:

- Metaplan and EASW, in a first stage, aim to collect proposals or future visions (which could be considered constraints, CAs, FRs) for the community. Afterwards, participants have to cluster and prioritize their ideas (establish a hierarchy), propose possible solutions (DPs) and identify the main responsible subject among stakeholders (PVs);
- Planning for Real aims to collect proposals (constraints, CAs, FRs) and to prioritize them through a public discussion (i.e. establish a hierarchy). Afterwards, a team of technicians adopts the outputs of the discussion as the inputs for a technical plan (which contains DPs and PVs).

If the lack of competences among the stakeholders is not managed, it seem problematic to demand participation in the whole design process from stakeholders (who usually are normal citizens) when using tools like Metaplan and EASW. Moreover, these tools do not provide detailed solutions or ways to implement them successfully. Metaplan and EASW identify only the stakeholder who has to be in charge of transferring their proposal into the daily life of the whole community. For this reason, the outputs of these tools cannot be sufficiently detailed to describe and solve all of the problems related to urban and territory planning. On the other hand, Planning for Real may provide more detailed outputs by demanding a detailed technical plan from a team of technicians. But it looks like an incomplete design approach: participants cannot check if their ideas are transferred to the technical plan correctly. Moreover, none of these approaches provide an assessment tool to evaluate the overall quality of the design process.

Axiomatic Design is not properly a technical tool: it is a general design framework which may be applied in many different fields. It requires expertizes and special skills to produce concrete and sufficiently detailed results for complex systems. And, it does not provide a tool for user needs (CAs) collection (Thompson 2013). This suggests applying methodologies that come from other disciplines. On the other hand, the Independence Axiom and the Information Axiom have been introduced to provide an assessment reference (Wilson *et al.* 1979).

A Possible Integration of Axiomatic Design in a Participated Planning Tool

Referring to the comparison between participated planning tools and Axiomatic Design, it is possible to assert that a quite strong complementarity between them exists. However, a management strategy for the lack of competences has to be provided.

The transition from the common top-down to the more effective bottom-up planning approach requires the active involvement of relevant stakeholders. Nevertheless this may easily bring facilitators and stakeholders to a "blank page" syndrome - "please, tell me what you want…" - without considering the impacts on the effective development of the territory due to a general lack of competences of the participants.

In the standard process, it is possible to identify that the technical competences of the stakeholders are inversely proportional to their decisional power (figure 3). For this reason, a standard participated approach could be easily be used just in the case of well-defined constraints and well-defined customer needs. Otherwise, the provided outcomes may be too general and the identified solutions may not be feasible.

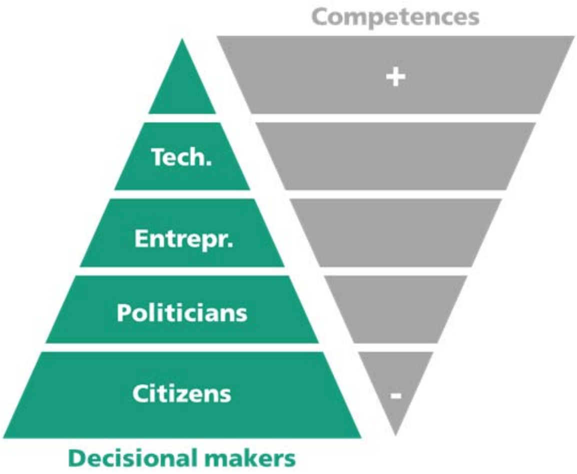

Figure 3. Technical Competences among the Stakeholders

Contrary to what participated tools suggest, it is possible to assert that constraints should be defined beforehand by technicians or by other stakeholders who are aware of the potentials and criticisms of the territory. Furthermore, constraints have to be very specific and fit the territory needs in order to avoid a "blank page" syndrome and to ensure the general sustainability of the final outcomes.

In order to push participated planning towards a standard use, Fraunhofer IEC is developing a new lean approach for participated activities by combining elements from the existing tools and Axiomatic Design. This approach foresees five main phases (figure 4):

Territory Analysis

A general study of the context has to be provided in order to identify potentials and criticisms of the territory as a whole. All changes (even the smallest) might create new problems in the system. It is not possible to waste resources. Only a deep consciousness of the consequences could ensure a strong sustainability of later decisions.

Scenario Definition

The strength of EASW tool is providing some predefined scenarios in order to set reference points and constraints clearly. This step is crucial to avoid the "blank page" syndrome and to sensitize stakeholders towards a consciousness vision of the territory. On the basis of the territory analysis, a series of scenario about possible future developments should be provided (no more than 4). These scenarios have to include some synthetic indicators, which provide basic information about the overall sustainability of the vision (e.g. from an economical, technical and environmental point of view).

Design of Solutions

Stakeholders have to rank the most interesting scenario and identify concrete solutions inside the selected vision. During this step, it is possible to apply a large number of approaches from existing tools to facilitate the creative process.

Assessment of Solutions

In order to ensure the fulfillment of territorial needs previously defined, a general assessment of proposed solutions has to be provided. Outcomes and possible adaptations also may be discussed with stakeholders.

Technical Design

At the end of the process, a team of technicians should adopt the outcomes as the inputs for the technical plan of the area foreseeing possible public discussions with stakeholders during design phases (preliminary, definitive and detailed).

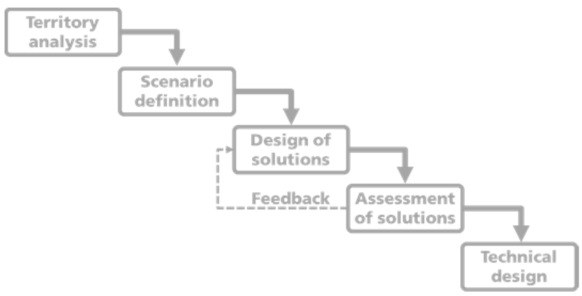

Figure 4. Overview of the Proposed Approach

Within these phases, an axiomatic approach may strongly improve the overall efficiency and it may ensure the objectivity of the outcomes and of the assessments.

The proposed approach foresees a stronger autonomy of technicians. It is important to highlight that the main intent is not to limit stakeholders' decision power, but to offset the general lack of competences and to raise awareness of the potentials and criticisms of the territory. It is possible to think about the Axiomatic Design implementation as a

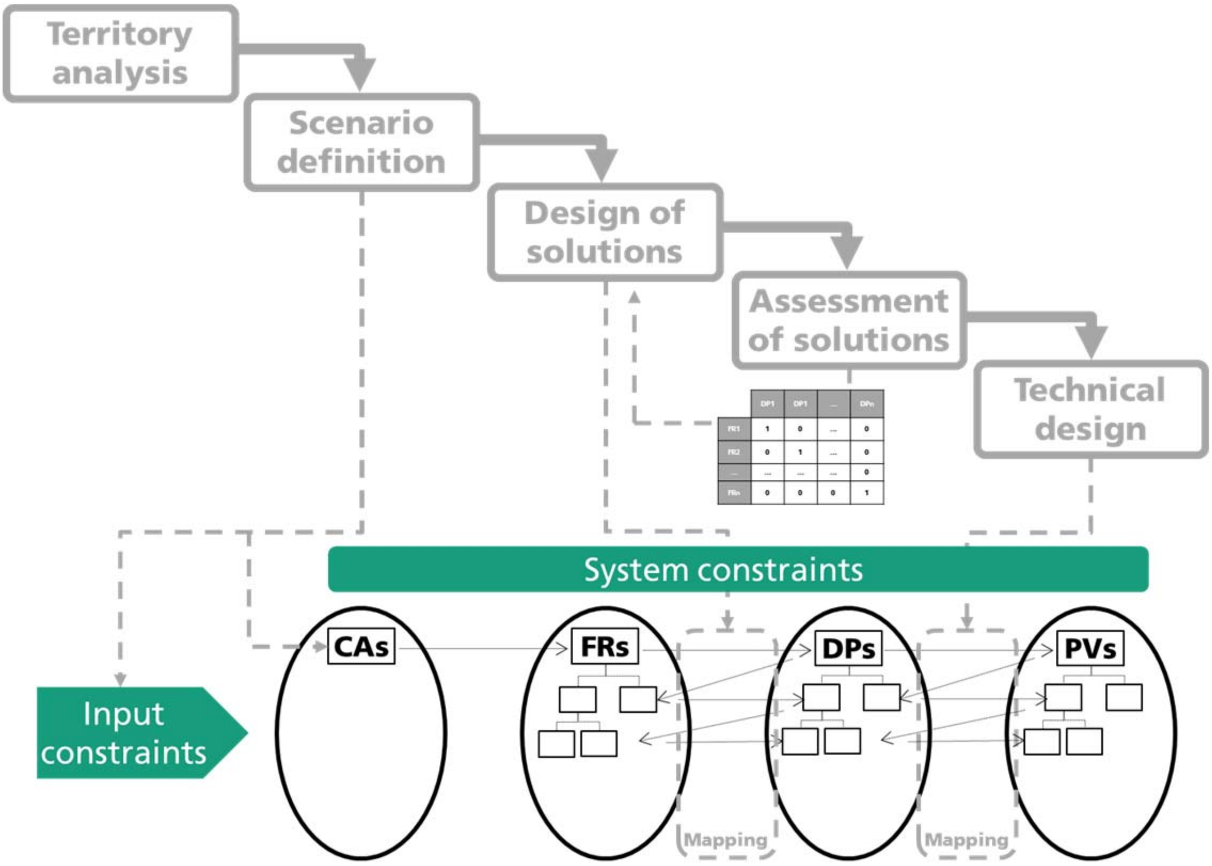

Figure 5. Parallelism Between the Standard Axiomatic Approach and the Participated Process

parallelism between the standard axiomatic approach and the process previously shown (figure 5).

Territory analysis is based on a multidisciplinary study of the context as a whole. The analysis has to include all the information needed to define development scenarios: demographic overview, the socio-economic situation, financial opportunities, etc. On the basis of the outcomes of the territory analysis, predefined scenarios have to be provided. These scenarios include all the information needed to start the AD process:

- Input constraints - The overall view of the possible future: intended use (industrial, tourism structure, hospital, green area, etc.), funding source (public, private or both) and maximum costs, etc.
- User needs (CAs) - On the basis of the intended use, the main user needs that must be satisfied must be clearly defined. This step may foresee interviews and discussion with the stakeholders related to the intended use.

System constraints have to be considered beyond the process. In urban planning, system constraints may be defined as: legal boundaries and limits, geometrical shapes (e.g. in case of refurbishment), laws of nature, etc.

These early phases should be entrusted to a group of technicians. Considering the large amount of information that has to be managed, a multidisciplinary group is recommended in order to provide outcomes with a higher level of detail.

Afterwards, a group of stakeholders has to be invited to rank the predefined scenarios and to discuss the identified user needs in order to set up a first set of FRs as starting point for the design process. In order to facilitate this process, standard participated tools should be adopted depending on the dimensions and on the typology of the group of stakeholders. Generally, it is possible to assert that the Metaplan and Planning for Real tools should be adopted for mixed stakeholders' group. The EASW tool should be selected only for specific stakeholder groups.

Due to the complexity in decomposition and mapping, the design phase should be entrusted to a group of technicians (including individuals experienced in AD) who are in charge of developing FRs and identifying DPs within the input constraints and the CAs of the selected scenario. In order to avoid a possible exclusion of stakeholders during this phase, it is important to foresee one or more public discussions of the outcomes from decomposition and from mapping (maybe with the same group involved during the scenarios' discussion). Through discussions, stakeholders could identify whether DPs are correctly answering to their needs, and suggest possible integrations before proceeding with the assessment of the design matrix.

Through the application of the Independence Axiom and the Information Axiom and the creation of the design matrix, a group of technicians could evaluate the overall design quality. According to Suh, an uncoupled design or a decoupled design should be preferred to a coupled one (Suh 1990). The decoupling process has to be discussed with stakeholders in order to identify possible solutions by mutual agreement.

Only when an uncoupled design is achieved, a selected group of technicians may proceed to the technical design and clearly establish PVs. In urban planning, PVs may be defined as technical plans which regulate construction activities across the territory.

Conclusions and Outlook

A participated governance strategy is one of the hardest challenges for the public administrations across EU states, especially in urban planning which strongly affects daily life, habits, economy, developments' strategies and the overall quality of life across communities. Referring to the Italian context, a lot of case studies have been developed by adopting the standard participated tools. Nevertheless, outcomes demonstrated that these tools seem incomplete for managing the planning and design process as a whole. The application of the Axiomatic Design approach could strongly improve the overall efficiency and the overall quality of the process, but some changes in the standard framework have to be introduced.

This paper investigates the opportunity to transfer AD in a participated urban process by carrying out a new approach which may fit AD's standard framework. Due to the lack of case studies, it has to be considered as a proposal. However, the proposed approach aims at discovering potentials and criticism in a participated approach. By comparing the proposed approach with the existing participated tools it is possible to assess that:

- Existing tools cannot manage a planning and design process as a whole with a high risk of lack in evolvement of stakeholders during key-steps.
- One of the greatest weak points of existing tools is the lack of an objective assessment process. Axiomatic Design could provide a strong assessment process through the definition of a design matrix.
- Constraints and CAs have to be thoroughly investigated within the scenarios development.
- Technicians' skill must be more solid than before. Strong expertise in AD is requested (decomposition, mapping and matrix assessment), during discussion, in order to avoid a deficiency of details or unfeasible DPs.

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From Analysis to Design: A New Computational Strategy for Structural Creativity

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Abstract: Since the introduction of finite element analysis software in the 1970s, structural engineers have become increasingly reliant on computational tools to carry out sophisticated simulations of structural performance. However, most structural analysis tools can only be used once there is a structure to be analyzed; they are not directly applicable in the design or synthesis of a new structural solution. This paper presents new research that expands the applicability of computation from structural analysis to structural design, with an emphasis on conceptual design applications. Specifically, this paper introduces a new interactive evolutionary framework implemented in a web-based structural design tool, structureFIT. This approach enables users to explore structural design options through an interactive evolutionary algorithm, and to further refine designs through a real-time analysis mode. This paper includes a critical background on optimization and its applications in structural design, an overview of the original interactive evolutionary framework, a description of the design tool, and a discussion of potential applications.

Keywords: Conceptual Structural Design, Structural Optimization, Computation, Evolutionary Algorithms.

Introduction

Conceptual Design of Architecture and Structures

In building design disciplines, including architecture and structural engineering, the design process is conventionally divided into four sequential phases: Conceptual Design, Schematic Design, Design Development, and Construction Documents. In practice today, major decisions regarding the building's geometry, massing, and overall form are usually made during the first phase, Conceptual Design (Hsu and Liu 2000; Wang *et al.* 2002). This phase is typically carried out by the architecture team alone, before strong involvement of engineering consultants.

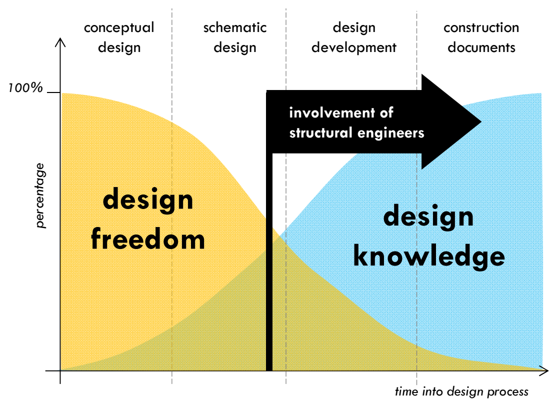

Figure 1. Relationship between design freedom and design knowledge in building design projects. After Fabrycky and Blanchard (1991) and Paulson (1976).

After the project has already taken shape, structural engineers and other consultants typically begin work, with the task of developing engineering strategies to enable the conceptual design vision, as illustrated in figure 1. This means that in standard practice, structural considerations are often subservient to architectural goals (Macdonald 2001). The design process is necessarily linear and unidirectional, and there are few opportunities for structural input to inform or improve the initial concept in significant ways (Holgate 1986).

Significance of Structural Form

History, theory, and nature show that for structural performance, overall form matters much more than material, member sizing, or internal topology (Thompson 1942; Zalewski *et al.* 1998; Larsen and Tyas 2003; Allen and Zalewski 2010). The geometry of a building's structure directly determines the distribution and magnitude of the forces it must resist (Macdonald 2001). Uruguayan structural designer Eladio Dieste (1917 – 2000) is quoted in an elegant expression of this point: "The resistant virtues of the structures that we seek depend on their form; it is through their form that they are stable, not because of an awkward accumulation of material. There is nothing more noble and elegant from an intellectual viewpoint than this: to resist through form" (Zalewski *et al.* 1998).

Today, with advances in a broad range of technologies, it is possible to design, analyze, and build forms regardless of their structural performance (Addis 1994). In fact, there is a recognized ingenuity in meeting the challenge of making a structurally poor forms work in spite of their inefficiencies (Macdonald 2001). However, this does not mean that this is the best way forward. This paper argues for and presents an alternate paradigm in which structural considerations are integrated into the form-making phase of the design process, conceptual design.

Existing Computational Design Tools

Today's architecture and engineering practices make widespread use of computational tools throughout the design process, and currently available tools both reflect and enforce existing design paradigms (Hsu and Liu 2000; Wang *et al.* 2002).

Geometry-based Tools for Architects

Architecture tools, starting with Computer-Aided Drafting programs in the 1980s, allow users to thoroughly document, and more recently generate, both conceptual and detailed designs. An increasing interest in complex geometry has led to powerful 3D modeling software which, coupled with scripting capabilities, enables the development of impressively complex forms.

Analysis-based Tools for Engineers

Computational tools for structural analysis mirror architecture tools in their power and capacity for complexity, and yet also maintain existing design roles. Finite element analysis (or FEA) programs are capable of determining stresses, deflections, and dynamic behavior for highly complicated geometry using very sophisticated techniques. Recent developments focus on increased accuracy and speed under a range of conditions. However, these tools are of little use in conceptual design; they require a geometry be provided to be analyzed, and are incapable of assisting with geometry generation. Again, these tools relegate engineers to the tasks of verifying the form and sizing the members, thus limiting or eliminating their involvement in conceptual design.

Key Structural Design Tool Features

The emerging research area of computational structural design tools seeks to bridge the gap between these existing computational approaches, enabling a true integration of structural input during conceptual design. This paper identifies two key types of features for such tools, feedback and guidance.

Feedback Features

A clear remedy for the lack of performance evaluation in geometry-generation tools is to integrate structural analysis capabilities into such software. It is critical that such analysis be fast, or ideally real-time, to allow for an interactive user experience. This type of feature shows users how design changes will affect structural performance according to metrics such as required material volume, structural stiffness, or estimated construction costs. This has been implemented in a number of applications both in research and practice, but is limited by the speed of computational structural analysis.

Guidance Features

To shift engineering software from the existing analysis and verification focus, tools for structural design should include form-guiding capabilities. This type of feature enables the software to suggest new geometries to the user in order to improve the structural performance of a design concept. While the field of optimization offers insight into ways to achieve this, there has been little progress in developing guidance-based tools for conceptual design both in research and practice. To truly encourage integrated conceptual structural design through modern computational tools, it is critical that methodologies that achieve this functionality be further developed.

Optimization in Structural Design

Structural optimization is a promising field with a rich history, but has nevertheless yet to make a significant impact on structural design in practice. This section explains the development of structural optimization theory and discusses the reasons for its disconnect with design.

The history of structural optimization can be traced back to Galileo Galilei (1564 – 1642), who in 1638 determined the optimal shape of a cantilevered beam subjected to a point load at its free end (Timoshenko 1953; Heyman 1998). By finding the parabolic profile, as illustrated in figure 2, Galileo showed that mathematics can be used to find forms that use material as efficiently as possible to support a given load. For many years since, this has been the goal of structural optimization.

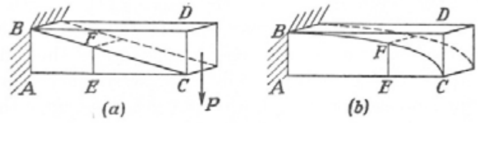

Figure 2. Drawings from Galileo's *Dialogues Concerning Two New Sciences* (1638), showing in (a) an incorrect linearly varying solution for the optimal shape of a cantilevered constant-width beam supporting a point load at its tip, along with (b), the correct parabolically varying solution (Timoshenko 1953).

Since Galileo, scholars have solved a steady stream of increasingly complex structural optimization problems (Wasiutynski and Brandt 1963). One of the most well-known contributions comes from Anthony G. M. Michell's work on another cantilever problem almost three hundred years after Galileo's original work. Michell showed how to find an optimal truss solution for the point-loaded cantilever problem (and a few others) in his seminal 1904 paper, "The Limits of Economy of Material in Frame-structures." Like Galileo, Michell was looking for minimal-material analytical solutions for key canonical problems, rather than offering a general approach for optimization of any structure. (Timoshenko 1953; Heyman 1998).

A more general approach that resembles methods in use today was developed in the 1960s, with critical work by Schmit (1960). A cohesive overview of work since is given by Spillers and MacBain (2009). In contrast with the analytical methods of scholars like Galileo and Michell, the new numerical methods attempted to find the optimum by iterating through potential solutions in a systematic way (Kirsch 1981). While iterative approaches were practically impossible in the days of manual calculation, the newly developed computers brought rapid calculations for large problems to reality.

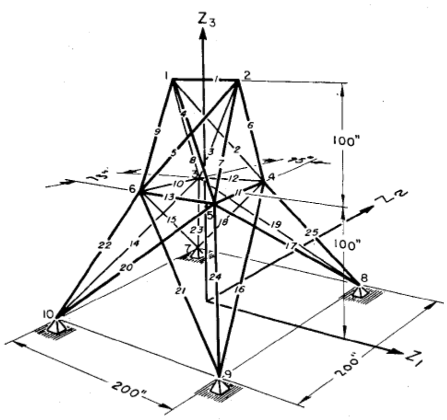

Figure 3. 25-bar trussed tower with member cross sectional diameters and wall thicknesses chosen by an optimization algorithm (Fox and Schmidt 1966).

Importantly, structural optimization researchers in the 1960s referred to their discipline as *structural synthesis* (Schmit 1981; Vanderplaats 2010), revealing the early aspirations of the field and evoking ideas of design in its truest sense: creating something new. However, the work actually dealt with choosing member cross sections for predetermined geometries and member configurations (Fox and Schmit 1966). For example, figure 3 shows a three-dimensional truss tower with 25 elements, whose cross sections were selected using a numerical weight minimization algorithm. This type of problem is referred to as size optimization. While improvements since the 1960s have broadened the reach of structural optimization strategies, the general disconnect between the goals and reality of structural optimization persist still today. In short, although structural optimization aims to generate new and exciting forms, most applications are limited to rather narrow problem spaces.

An important step forward in structural optimization was the development of shape optimization, or the determination of overall structural form as opposed to element sizes (Vanderplaats 1982; Bennett and Botkin 1986; Haftka and Grandhi 1986). Most applications of this early work were in structural design of components in the automotive and aerospace industries, where an improved part would be used hundreds or thousands of times, yielding extensive savings, although there are also examples of shape optimization for trusses, sometimes called geometry optimization. Because it deals with overall form, shape optimization is more relevant to conceptual design than size optimization.

The third type of structural optimization used today is topology optimization, or the optimal connective arrangement of elements in a structure, developed numerically in the late 1980s (Bendsøe and Kikuchi 1988; Rozvany 2001; Rozvany 2007). This type of optimization can also be integrated with shape optimization and size optimization.

Specific methods have been developed to address each of the three classes of structural optimization problems, but in general they share a common formulation, described in the following subsection.

Optimization Problem Formulation

Formally, structural optimization is a numerical method of finding the best solution according to mathematically formulated functional requirements, or objectives, while conforming to mathematically formulated constraints. The solution is expressed in the form of numerical values for a design vector, x, which represents a list of design decisions to be made – for example, nodal positions, material selections, cross sections – called design variables.

The objective function, $f(x)$, is often a calculation of the weight or volume of the structure, such that a minimal-weight structure can be found. However, this function can also consider stiffness, strain energy, deflection, or other quantitative goals, structural or otherwise. The constraints, $g(x) \leq 0$ and $h(x) = 0$, and the variable bounds, $x_{i,lb}$ and $x_{i,ub}$, restrict the solutions according to design or behavioral requirements. More specifically, design constraints can represent geometric or spatial requirements, constructability or fabrication limitations, or other functional considerations. Behavioral constraints set limitations on structural behavior, and include restrictions on performance metrics like internal stresses, deflections, or buckling capacity (Kirsch 1981).

Together, the design vector, constraints, variable bounds, and objective function define a design space, or solution space, for a given problem. The dimension of this space is given as one more than the number of design variables, to represent the space of possible design vector values and their resulting objective, or performance, values. Structural design problems often have design spaces that are large and complex, although the exact nature of the design space depends on the specifics of the problem.

Limitations of Optimization in Design

Despite the rich academic history of structural optimization, it has had relatively little impact on structural engineering in practice. Fundamentally, this can be attributed to an inherent difference in goals between optimization and the design of buildings. While optimization is necessarily a convergent process, or one in which an iterative and systematic algorithm converges upon a single solution, design is decidedly divergent. In design, it is recognized that a variety of significantly different yet suitable solutions can be found from a single starting point.

Moreover, the exercise of mathematically formulating objectives and constraints is difficult or impossible in the design of buildings. Many goals and requirements are qualitative, or even subjective, such as visual impact, spatial experience, contextual fit, and overall architectural value. Since most structural design cannot occur in the absence of architectural goals, this presents a significant challenge.

In addition, the design process for buildings is often one of discovery: designers do not know all of their objectives and constraints at the beginning of the process, but develop them as they explore design possibilities. The designer’s interaction with the process of evaluation and iteration is key. In contrast, standard optimization is a relatively rigid and automated process in which goals and requirements must be enumerated completely at the start. Unlike the human design process, optimization on its own cannot handle unformulated objectives and constraints.

Finally, most structural designers lack intensive training in optimization, and there are few tools or approaches available that make optimization accessible to non-experts. Furthermore, optimization tools that do exist are often text-based or severely limited in their graphical displays, and often rely on piecing several pieces of software together. Human designers are necessarily highly visual, and can process and evaluate information much more quickly and fully when it is presented graphically. Therefore, in order to be useful for designers in practice, tools that use optimization should be easy to use, integrated, and strongly graphical.

Interactive Design Space Exploration

Given the issues with standard optimization in conceptual structural design, it is necessary to look beyond the established approaches to find ways to bring computational design guidance to conceptual design tools.

Interactive optimization addresses this issue in a simple but compelling way: the designer is allowed to interact with the computer algorithm in deciding which designs to pursue in the iterative optimization process. The exact mechanics of the interaction depend on the specific algorithm chosen. In general, the interactive element allows the user to only partially formulate the design problem in a quantitative way, and to use unformulated or newly discovered objectives and constraints to make design selections.

Interactive Evolutionary Algorithms

Evolutionary algorithms are a general class of optimization strategies that use the principles of Darwinian natural selection to grow and evolve populations of designs. They have the advantages of being robust and well-suited to complicated engineering problems. Because they incorporate randomness, they avoid getting stuck in local optima, and can effectively hop around the design space in search of better solutions.

Furthermore, because they work with populations of candidate designs, evolutionary algorithms are especially useful in promoting design diversity. Unlike algorithms that focus on improving singular solutions, these algorithms improve a group of alternative options as they iterate. The general procedure is to randomly initialize a first generation, evaluate the fitness of each member of the generation, identify the top performers, and use those to create a subsequent generation by combining and mutating them. In standard evolutionary algorithms, the process runs automatically until preset criteria are reached, and a single solution is presented as the optimum. However, it is also possible to take better advantage of the design diversity created by this approach by incorporating human interaction.

On their own, evolutionary algorithms are subject to the same criticisms as other standard optimization approaches, as detailed previously. However, because of their population-based approach and selection mechanics, evolutionary algorithms lend themselves particularly well to human interaction. Interactive evolutionary algorithms are a subclass of optimization algorithms that use principles of evolution combined with human input to drive design space exploration. The general iterative process for this type of algorithm is illustrated in the diagram in figure 4. The cycle differs from standard evolutionary algorithms at the design selection step. The algorithm identifies top performers, but solicits input from the user to make final choices about which designs to proceed with to form the subsequent generation. This key difference allows the designer to adjust the optimization process based on unformulated goals, such as visual impact or constructability requirements. Furthermore, the user may adapt goals across generations, based on newly realized design criteria discovered in the explorative process.

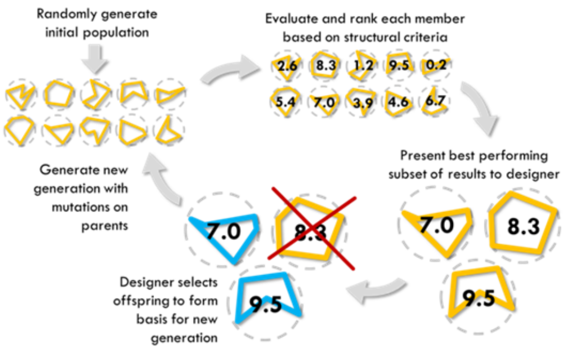

Figure 4. General diagram of an interactive evolutionary algorithm, including the interactive step highlighted in blue.

The first interactive evolutionary algorithms were developed in Sims (1992) for the purpose of finding visually interesting cellular automata. In this early case, selection was entirely based on user preferences, rather than on a combination of user preferences with calculated objective functions. The literature includes many subsequent examples of this strict type of interactive evolutionary algorithm, including for the design of web pages (Oliver *et al.*, 2002) and coffee blends (Herdy 1997).

Contributions from Parmee and collaborators led to some of the first interactive evolutionary algorithms that used both computation and human input to drive selection (Parmee 1997; Parmee and Bonham 2000; Parmee 2001). Unlike the earlier examples, which focused on design problems with highly subjective performance metrics, this work is in the realm of engineering, which has both quantitative and qualitative goals. This work laid the foundations for further research in the applications of interactive evolutionary computation to structural design.

More recently, some progress has been made in applying interactive evolutionary computation specifically to the realm of structural design. Most notably, von Buelow has proposed an interactive genetic design tool for creative exploration of design spaces, including for the design of trusses (2008) and folded plate structures (2011).

Specific Needs

Existing work suggests specific challenges to be addressed by a new interactive evolutionary framework. First, existing approaches implement interactivity in limited ways. Interactive features should be expanded to allow more incorporation of requirements and criteria from the designer. These features can also help the designer direct exploration of the design space in a more precise way, further improving the effectiveness of an interactive evolutionary approach.

Additionally, existing research treats interactive evolutionary algorithms as a stand-alone approach without considering the broader user design experience. There is a need to incorporate general problem setup strategies and design refinement functionalities into an expanded approach, along with the evolutionary approach itself.

The framework presented in this paper is a novel holistic approach that generalizes the use of interactive evolutionary algorithms in conceptual structural design, and also addresses these specific needs.

Interactive Evolutionary Framework

This section introduces a novel framework that adapts a generalized interactive evolutionary algorithm for conceptual structural design, as well as its implementation as a software tool. Detailed descriptions of specific original features of the framework are discussed more fully in subsequent sections.

Framework and Software Architecture

Existing work suggests specific challenges to be addressed by a new interactive evolutionary framework. First, existing approaches implement interactivity in limited ways. Interactive features should be expanded to allow more incorporation of requirements and criteria from the designer. These features can also help the designer direct exploration of the design space in a more precise way, further improving the effectiveness of an interactive evolutionary approach.

The software implementation of this framework reflects its generalized nature. The program is written in C#/.NET (Microsoft 2012), an object-oriented programming language, and is designed to be modular and extensible. There are four general types of backend classes: variables, design models, structural analysis engines, and the interactive evolutionary algorithm population generator. The population generator connects with a graphical user interface to allow input from the user. The interaction of these parts is illustrated in figure 5.

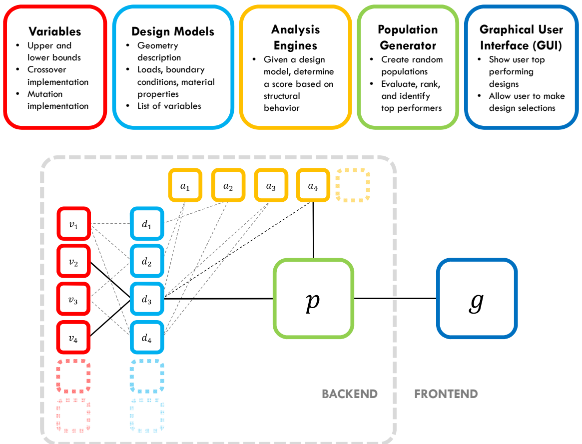

Figure 5. Software architecture diagram for the interactive evolutionary framework, illustrating main class types and interactions.

This diagram shows the versatile nature of the framework. Variables, design models, and analysis engines are all designed using interfaces, meaning that each can be implemented as a variety of types. For example, variable types can be horizontal and vertical nodal positions, but they could also be material properties, joint fixities, member topologies, or other design decisions. Design models can be truss structures, again as introduced previously, but they could also be frame structures, continuous solid structures, or other structural types. A design model type must have one or more analysis engine type that can apply to it. For example, truss structures are associated with a truss analysis engine, but could also be analyzed by more detailed analysis engine types. Examples of variable types, design model types, and analysis engine types are presented in the following subsections.

The population generator works with a particular design model type and a particular associated analysis engine type. Using the design model and its variables, it creates a generation through crossover and mutation. Using the analysis engine, it applies a fitness score to each candidate design. It then presents the best designs to the user through the graphical user interface, which also allows the user to make selections. These selections are sent back to the population generator, which produces a new generation.

Variables and Design Models

As discussed in the previous subsection, the interactive evolutionary framework supports multiple variable types and design model types. To illustrate how these classes work, the example of a truss design model with variable nodal positions will be used. Figure 6 shows a seven-bar truss with three design variables. The truss model is defined by its nodes and members. Nodes are defined by degrees of freedom, which have coordinates, loads, and supports. In this two-dimensional case, nodes have two degrees of freedom. Members are defined by their start and end nodes and their material properties. Like all design model types, the truss model also has a vector of variables. This is the model's design vector, or parametric representation.

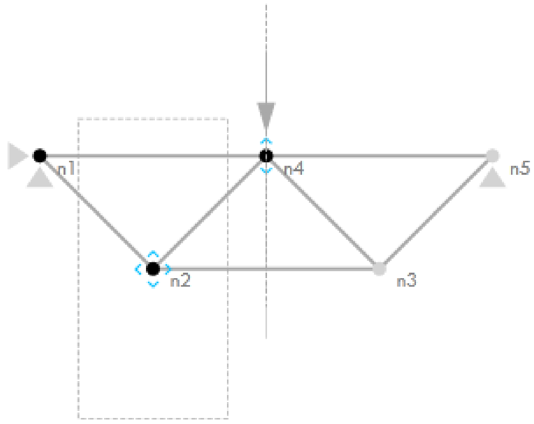

Figure 6. A planar seven-bar truss design problem with three design variables: the horizontal and vertical positions of the lower left node (n2), and the vertical position of the central node (n4). This truss is simply supported, has a central point load, and is bilaterally symmetrical.

In this type of design problem, the coordinate of each degree of freedom can be a variable. Any variable type must have defined upper and lower bounds. In this case, the upper and lower bounds are the allowable range for the coordinate, illustrated in figure 6 with the dashed rectangle for node 2 and line for node 4.

Additionally, any variable type must implement analogues of the biological concepts of crossover and mutation. Conceptually, crossover combines encoded information from more than one parent to create offspring that have traits from each of them. Mutation then randomly perturbs the newly formed offspring in order to encourage diversity. For this example, the implementations of mutation and crossover are given in Eqs. (1-6), and apply to continuous variables in general beyond the degree of freedom coordinate. Crossover is accomplished through a weighted average of seed variable values with random weights. Mutation updates a variable value with a random variable from a normal distribution with a standard deviation related to the variable's allowable range and set mutation rate. For discrete or integer variables, these same approaches can be used with minor modifications.

Crossover: $$x_{\text{crossed}} = \frac{\sum_{i=1}^{n} x_i w_i}{\sum_{i=1}^{n} w_i} \quad (1)$$

Mutation: $$\mu = x_{\text{crossed}} \quad (2)$$

$$\sigma = \frac{|x_{\text{ub}} - x_{\text{lb}}|}{2} r_{\text{mutation}} \quad (3)$$

Normal distribution: $$f(x;\ \mu, \sigma^2) \quad (4)$$

$$x_{\text{rand}} = \text{rand}(f) \quad (5)$$

$$x_{\text{mutated}} = \min(\max(x_{\text{rand}}, x_{\text{lb}}), x_{\text{ub}}) \quad (6)$$

The framework also supports parametric relationships between variables and non-variables. For example, the truss design model presented here allows for mirror and offset relationships between degree of freedom coordinates. The former is illustrated in the problem shown in figure 6, which uses bilateral symmetry to define the position of the lower right node (n3) based on the position of the lower left node (n2).

Analysis Engines

Design model types must be associated with at least one analysis engine type, although the framework supports the use of multiple analysis engines. Any analysis engine must determine a quantitative fitness score for a given design model, based on structural criteria. For example, in the case of the truss model, a truss analysis engine can find the required volume of a structure with a given geometry, loading, and support conditions. The engine calculates this metric as follows: compute the forces in each member using the direct stiffness method, assign required cross sectional areas to each member based on allowable stress and buckling considerations, and find the sum of the area lengths times their required areas.

The code for this truss analysis engine was written from scratch, using the open-source Math.NET numerical analysis library for matrix operations (Math.NET Project 2012). However, analysis engines could also make use of commercial structural analysis codes. An important note is that for statically indeterminate structures, this particular process is affected by initial member sizes used to compute forces. In this case, optimal member sizing can be computed through iteration, or an approximate result found through initial equal member sizing can be accepted.

Population Generator

The population generator in this framework implements a simple and flexible interactive evolutionary algorithm that can be easily controlled by the user and adapted to a wide range of variable, design model, and analysis engine types. As explained previously, the interactive evolutionary algorithm is an iterative approach that can be repeated until the user is satisfied.

The first step of the algorithm is to generate a random population of a preset number of candidate designs. For the first generation, this is based on random perturbations from an initial structure defined by the user. Specifically, for each candidate design in the new generation, each design variable is mutated from initial values from the user-defined initial structure. Mutation is carried out in the manner previously discussed, and illustrated in Eqs. (2-6) for the example of continuous variables.

Next, the algorithm uses the analysis engine to assign a fitness score to each candidate design. The algorithm then sorts the designs according to this score and presents a top-performing subset of designs to the user through the graphical user interface. The user is then able to visually evaluate the designs and choose those that best meet the qualitative or otherwise unformulated goals for the design process. The designs that the user chooses are used as seeds for creating the next generation in the iterative process.

The seeds are used to form a new generation using the previously discussed crossover and mutation functionalities. The newly formed generation of new candidate designs is then evaluated, sorted, and presented again, and this process can continue as long as the user wishes. There are also several ways for the user to interrupt the process. If the user does not like any of the presented designs, or wishes to make changes to designs previously selected, the user can return to a previous generation, adjust selections, and rerun the algorithm from that point. Also, the user can choose to select no designs, and the algorithm will reset and start with the previously defined initial structure once again.

User Experience and Interface

The framework described above has been implemented in an interactive proof-of-concept design tool called structureFIT (Mueller 2013). The following sections describe the graphical user interface and general user experience.

Graphical User Interface (GUI)

The graphical user interface (GUI) enables the interactive step of the interactive evolutionary algorithm by showing the user top-performing designs graphically and allowing the user to make selections. The GUI is implemented using Silverlight, a platform-agnostic technology that supports interactive user applications that run in a web browser (Microsoft 2012). There are several advantages to this approach, in comparison with traditional desktop applications or integration into existing software. First, the program is highly accessible: anyone with a web browser can use it, regardless of operating system, and there is no need to download or install it. Second, there is no need for the user to own other commercial software, such as Rhino or AutoCAD, to run the program, and the program is not tied to software trends, which tend to change relatively quickly in the architectural computation realm. Finally, the web-based interface lends itself naturally to analysis calculations on remote servers. While all calculations are currently executed on the client-side, or on the user’s computer, future use of server-side calculations through remote resources or cloud computing could significantly improve performance.

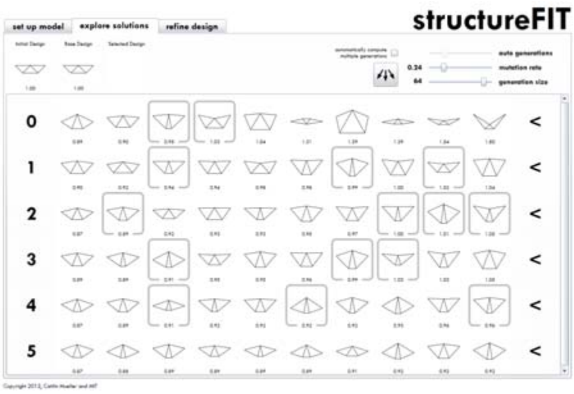

Figure 7. Screenshot of the web-based graphical user interface, showing the evolution of solutions for the design problem presented in figure 6.

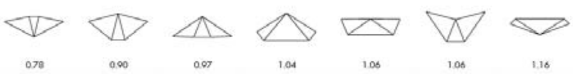

Figure 8. A closer view of several candidate designs created by the population generator and presented to the user, with scores normalized by a base design’s score shown underneath each.

A screenshot of the GUI is shown in figure 7. It is designed to be simple and user-friendly, while still allowing for powerful user control. The main feature of the interface is the matrix of designs, shown in numbered rows. Each row represents a generation created by the population generator, and the designs shown are the top ten performers. The number under each design corresponds to its score, normalized by the score of a base design, which is shown, along with the initial design, in the upper left-hand corner of the interface. Designs with scores less than 1.00 perform better than the base design, and those with scores higher than 1.00 perform worse. A closer view of generated designs and their scores is shown in figure 8. After each generation is produced, the user is able to select zero, one, or more designs by clicking on them, and selected designs are indicated with a gray square. The user then clicks the main “generate” button to produce a new generation.

The user can return to a previous generation by clicking the “<” button next to the corresponding row. This will erase the designs generated since, and the user can change the selected designs and rerun the computation. The user can also adjust the mutation rate and population size for each generation, and can choose to turn on a hybrid approach that automatically computes several generations in a row. These features are discussed in more detail in subsequent sections.

Expanded User Experience

In addition to the interactive evolutionary design experience, this framework includes original functionality that can be used before and after. Before evolutionary design exploration, the user can set up the design problem by drawing in a graphical and intuitive user interface. This makes the framework general beyond specific examples. After the evolutionary design evaluation, the user can refine an evolved design using real-time performance feedback. These additional features help bring this framework beyond an algorithm and toward an approach usable for real design problems.

The design setup mode allows the user to define a design problem by building a structural model and identifying variables. The user can draw a structure by clicking and dragging to create nodes and members on a canvas, or by modifying entries in an adjacent spreadsheet. The user can then assign loads and supports to defined notes, and define variables, including upper and lower bounds. Finally, the user can define planes of symmetry and parametric relationships, including mirror and offset relations. The information entered by the user is updated dynamically in the graphical view of the structural model. This functionality is illustrated in figure 9.

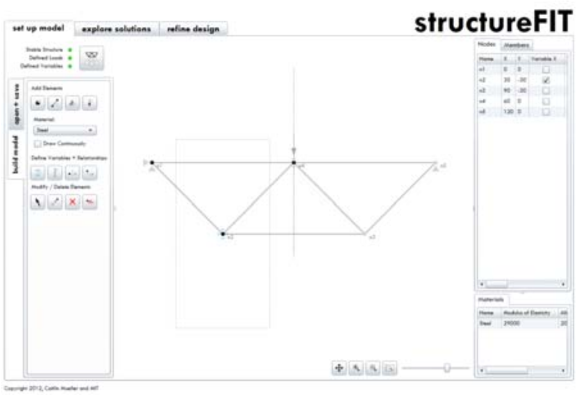

Figure 9. Screenshot of the model setup mode, in which the user can input a design problem, specified by structural geometry, loads, materials, boundary conditions, and variable definitions.

The user may also choose to open one of a range of preset design examples that can be run directly, or modified to adapt to new problems. Additionally, the user can choose to save a custom setup structure that can be opened again later in the design session. Once the setup structure has been finalized, the user can click the button in the upper left of the screen to set it as the initial design for the interactive evolutionary mode. If the structure is not stable, or contains no loads or variable definitions, the program will identify these issues for the user to correct.

This setup mode is important because it makes the interactive evolutionary framework both highly flexible and easy to use. The framework is not tied to any particular example or case study, and can be used by designers for real design problems. Additionally, the GUI for design input is powerful and user friendly, so that designers can define problems quickly and move on to exploring solutions in the interactive evolutionary mode.

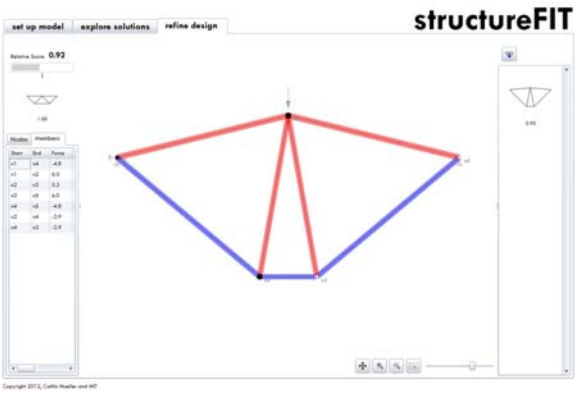

Figure 10. Screenshot of the design refinement mode, in which the user can adjust designs found in the interactive evolutionary exploration with real-time performance feedback in terms of the overall score and individual member sizing. The members are drawn with required thicknesses shown to scale, with blue indicating tension and red compression.

Once the user has found an interesting design, it can be studied and refined further in the design refinement mode. This mode allows the user to graphically adjust variable settings for a selected design to fine-tune its appearance, while also receiving real-time feedback on the performance implications of the adjustments. In the case of nodal coordinate variables, the user is able to adjust the nodal positions by clicking and dragging, and note the change in the overall design score. The program also instantly updates the required thickness of individual members, shown graphically on the members themselves and numerically in a spreadsheet. The user is able to save particular designs found in this design refinement mode and return to them for comparison. Once an attractive solution is found, the user can export it for use in more advanced modeling and analysis software. A screenshot of this design mode is shown in figure 10.

Like the model setup mode, the design refinement mode adds crucial functionality to the interactive evolutionary framework. By combining a guidance-based approach with a feedback-based post-processing step, the framework is able to expand design freedom for users.

Conclusions

This paper has presented a general framework for using interactive evolutionary optimization in conceptual structural design. This work is important because it helps enable a guided exploration of structural design spaces, while still allowing for creativity and freedom, addressing the issues found in standard optimization previously identified.

This framework builds upon existing work in interactive evolutionary algorithms and in structural design tools, addressing specific issues that remain unresolved in previous literature. The specific contributions include the generalized approach for interactive structural design as well as its graphical and interactive implementation in the form of the structureFIT design tool.

Applications

The framework and tool introduced here could significantly improve conceptual design exercises in practice, as a way to generate and compare a wide range of design ideas quickly and easily. An architect with basic structural knowledge could use the tool alone or as a supplement to working with a creative structural engineer early in the design process. A structural designer could also use the tool to develop innovative structural concepts to discuss with the architect for further development. In a more integrated approach, a team of architects and engineers could use the tool together during conceptual design, collaboratively developing design alternatives that perform well structurally and achieve architectural design goals. Finally, the tool could be useful in facilitating discussions between designers and clients, helping clients understand tradeoffs between options and cost implications of design ideas at the earliest stages.

Possible applications in the classroom mirror those in practice: architecture students could use a tool implementing this approach for exploring early design options for studio projects, and engineering students could use such a tool for engineering design projects. However, the design tool also has additional didactic potential for developing intuition for structural behavior in architecture and engineering students, a very important and increasingly neglected aspect of education in both disciplines. For engineering students, this tool could also offer a way to encourage design creativity, another significant but overlooked area. Furthermore, a tool used by students from both disciplines together would foster collaboration and improve students' cross-disciplinary communication skills, which are much needed in practice.

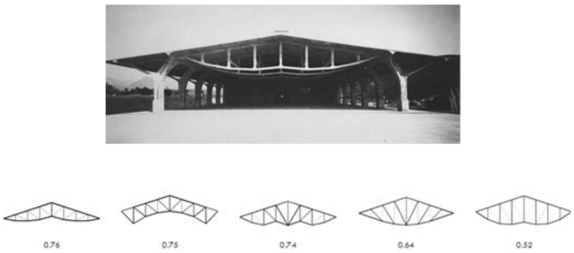

Figure 11. Robert Maillart's 1924 design for a shed roof in Chiasso, compared with designs discovered using the computational approach presented in this paper.

In addition to discovering design possibilities for new projects, this approach could also be useful in studying existing work within the context of a formal design space. Most architectural history research does not include detailed analyses on structural performance, which can be of value in evaluating success and identifying lessons to move forward with. The design space strategies used in this approach allow researchers to consider a historical work as a point in a space of alternatives of varying structural performance and formal attributes, potentially gaining insights on design decisions and process. For example, Robert Maillart's concrete shed roof in Chiasso, Switzerland, designed in 1924, is shown in figure 11, along with related design alternatives explored using the approach presented in this paper. It is evident that there is a family of solutions of varying performance, some of which share more in common with Maillart's design, which achieves a constant force in the gable elements, and some less. Such a study could provide a new context through which designs could be analyzed, understood, and revisited in the future.

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Reflections on How DGNB(UD) Certification Standards Effect Design Methods

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Abstract: DGNB is an abbreviation of Deutsche Gesellshaft für Nachhaltiges Bauen, a German sustainability standard and certification system that has operated for a decade and that was appointed as the official Danish system by Green Building Council (GBC) Denmark in 2009. In 2012 GBC Denmark launched a second DGNB standard, now focusing on urban districts. This certification standard is currently still in the process of being adjusted to Danish standards. DGNB Urban Districts (DGNB(UD)) pleads for using their system as design 'tool' or guideline for the very early design stages. This process has not been investigated or described well. In this paper, the effect of DGNB(UD) on design is investigated in a case study using DGNB(UD) as a 'design tool'. The effects on the design process is observed and compared to well established methodologies of integrated energy design (IED) and traditional beaux- arts architectural design. The case study addresses the design of an abandoned harbor area to be re-inhabited and to provide new functions.

Keywords: Design Method, Sustainability, Certification System, DGNB, Integrated Energy Design, Urban Planning.

Introduction

A Paradigm Shifts from Energy Matters Towards a Holistic Understanding of Sustainability

When the EU standard of Environmental Impact Assessment was implemented, it profoundly affected the design of infrastructure and other civil engineering projects. The broad and complex directive dictated that aspects other than traditional civil engineering issues should be addressed, thus invited architectural offices to take a more central role in the design process.

Civil engineering systems are present behind the scenes in urban design and will be affected by new ideas of urban design. For example, there is a tendency towards natural systems (for instance handling of rainwater and greywater locally) instead of complex mechanical systems. The sustainability certification system of urban districts, DGNB(UD) (www.dgnb.de) thus, implicitly provides a new framework for civil engineering systems because many of its 45 criteria implicitly address the above mentioned paradigm shift. The focus of this paper is not to investigate the design of large scale structures and civil engineering systems, but on a more general basis it looks into how technical scientific knowledge is integrated in a design process when exposed to the framework of a sustainability certification system in an urban scale.

The DGNB(UD) system is comprised of 45 criteria from 5 major areas (the DGNB System). A large part of the criteria concerns technical-scientific matters, and design methods for integrating these in architectural design have been researched for two decades in the framework of Integrated Energy Design (IED) Methodology. IED is a family of related design methods that address how the design of buildings can be informed by technical scientific knowledge from the earliest design phases and onwards with the aim of reducing energy consumption for operating buildings (Hestnes *et al.* 2008).

IED is operational today, after two decades of continuous advancement in facilitating software. IED is limited in the number of parameters that vary in the design process because the focus is on reducing energy consumption for operating buildings (heating, cooling, ventilation, lighting). This precise goal has made it widely applicable.

Architectural Design processes are not informed by the necessary technical scientific knowledge. This makes meeting sustainability demands a result of chance or later adjustment. The resourcefulness in architectural design methods lies in the ability to create ideas of form from zero.

However, the DGNB(UD) has a broader and complex focus, which challenges both IED and existing Architectural Design methods. Using DGNB Urban Districts (DGNBUD) as a framework for design work implies a step into a broader realm, with a multitude of parameters, most of which are not yet facilitated by adequate software.

Focus on the reduction of energy needed to operate houses limits a perspective for the future. We can already limit the energy we use for operating houses to zero. The focus will thus turn to the embodied energy in existing structures, materials and LCA of materials. Social and economic issues and issues of toxicity and health will also find a place in a broader design process. Trying DGNB(UD) out as a sort of design tool or method is thus a step into a design method of far larger complexity than IED.

We know from research that the urban design is determining a large part of the energy profile of a building (Strømann-Andersen 2012). We also know that climatic comfort in urban spaces influence the use and thus have an effect on the social characteristics of the city (Gehl 2010).

A framework for forming a design method in regards to the above mentioned is a need. This makes it worthwhile to try out DGNB(UD) as a design tool because DGNB(UD) has the broadness required for the next generation of integrated design processes.

Hence, this paper asks: can DGNB(UD) generate ideas and form and is it operational in a design process as the DGNB organization urges designers to do?

Method: DGNB (UD) as a Design Tool

Case Study – The Paper Island Development, Copenhagen

A preliminary hypothesis of the paper is that DGNB(UD) can be used from the earliest design stages in the design of large scale structures and urban spaces. The DGNB(UD) society suggests that it is to be used to provide design guidelines from the earliest stages. In an exploratory case study, DGNB(UD) is investigated as a generator of design guidelines from the earliest of design stages. In what sense does it make the design process different from traditional architectural design and Integrated Energy Design (IED)?

The effect of the DGNB(UD)-influenced design method is observed and compared to the well-established methodologies of integrated energy design (IED) and architectural design.

Architectural Design

Architectural design is outlined by the beaux arts tradition where the design process is organised by a ‘zooming’ in scale (Shawe-Taylor 1993). Before the founding of first architectural academies in the late 17th century, the builders referred to construction tradition and classical canon (Vitruvius). In the Beaux-Arts tradition, this knowledge was systematized and taught in a master–apprentice relationship at the ateliers (Prentice 1985). In the 20th century, the modern movement who placed emphasis on intuition challenged the Beaux-Arts system. In the Bauhaus academy, the first year was reserved entirely for artistic exercises in exploring the design potential deriving from a subjective and intuitive approach (Findeli 1991).

In this paper, the architectural design tradition is defined as the systematic ‘zooming’ in scale controlled by architectural meaning (story behind the concept) and giving form based on the architect’s intuition and experience.

Integrated Energy Design (IED)

There is a multitude of IED concepts, which address these subjects:

1: Process focused methods (how to work in multidisciplinary, integrated design teams, what to consider when and by whom).

2: Design evaluation methods (structured evaluation of potential design solutions, design criteria).

3: Information about the design process by (simulation) software. What to apply and in what order and how to integrate the results in the ongoing design process (Petersen 2011).

The design of buildings with the aim of reducing the energy demand for operating is the classic topic of IED. This paper presupposes a multidisciplinary team for both the IED and DGNB(UD) process (not in relation to the architectural design method). IED is defined as a systematic parameter variation, evaluated and informed by simulations. This processes moves forward in a series of iterations structured in 3 tempi: reduce (energy consumption), optimize (HVAC systems) and produce (energy) (Eurima, web).

The case study is a real urban development of an abandoned harbor area to be re-inhabited and to perform new functions in Copenhagen, Denmark. This case study developed around 3 main phases: the initial phase, the layout of the site, and the design of building volumes.

Figure 1. The Location of the Paper Island in the Inner Harbour of Copenhagen

Figure 2. The Current Look of the Paper Island

Figure 3. The Present Distribution of Functions in Close Proximity of the Paper Island

Initial Phase

The methodological framework inspired by DGNB(UD) is set up, and the final approach is decided to be a multidisciplinary approach loyally structured by the relevance of singular DGNB(UD) criteria. Specialist team meetings and interviews were conducted to inform the design decisions, and traditional architectural design methods and DGNB(UD) influence on the design process are observed and compared.

Layout of Site

An iterative design process based on the DGNB(UD) criteria was carried out. Quantitative and climatic design parameters interacted with qualitative design decisions based on specialist input. The influences of Architectural Design methods and DGNB(UD) on the design process are observed and compared.

Design of Building Volumes

Similarities and differences between IED, Architectural Design methods and DGNB(UD) and their influences on the design process are observed and compared to meet a conclusion as to the relevance of DGNB(UD) as a design tool.

Findings: Case Study: Paper Island

DGNB Urban Districts and its Potential as a Design Tool

Initial Phase

The Paper Island in the Inner Harbour of Copenhagen (figure 1) is an artificial island of 22.000 m^2 developed to facilitate naval activities from 1740 and onwards (Rasmussen 2009). Since the 1930s, the island has served as a storage area. This function has been unchanged for almost a century despite the central part of Copenhagen developing around the harbour and thus out-phasing the industry (figure 2). During the past decades, intense discussions on the use of the island and its integration into the urban fabric have had a significant place in the public debate (Juul Nielsen, 2012). In 2012, the island was the only remaining industrial function in the area, and in November the company announced its sudden withdrawal from the contract, leaving the buildings with no purpose. Once again public debate was launched; this time more present than ever due to intense public and private investments in the area and its new status as an “experience landscape” with the Opera House, the Playhouse and other major cultural institutions as its neighbours (Juul Nielsen, 2012).

Thus, the first task was the programming of the area (figure 3). The choice of new functions for the area affects the ability to meet the DGNB(UD) criteria. Interviews with stakeholders were organized to inform those demands also described in DGNB(UD) criteria 38 *Participation*, 39 *Concept development process* and 41 *Municipal involvement*.

The dilemma concerning social diversity in DGNB(UD) criteria 16 *Social and Functional Mix* and economical balance in DGNB(UD) criteria 13 *Fiscal Effects on the Municipality* and 14 *Value Stability* is addressed in a new book by Gehl Architects, Urban Spaces as a Platform for Growth (Gehl, 2012), which inspired the choice of possible stakeholders to be interviewed as the publication had a holistic view on urban development by integrating both business functions and residential opportunities. The stakeholders interviewed were an urban planner from the Copenhagen municipality responsible for the area, the project manager of the Gehl publication as well as the CEO from the urban development project *Kvaesthusprojektet*, where private investors are investing in a subterranean parking space with a recreational urban square to service the playhouse and the urban area around the historic center of Copenhagen (www.kvaesthusprojektet.dk).

Based on this process, a spread of functions, their location on the site and the priority they were to receive in the project concerning square meters were proposed. It was determined that the chosen combination of functions would enhance the compliance with several DGNB(UD) criteria within the social, the economic and the environmental categories.

The mix of functions chosen was by the qualitative interviews carried out with the stakeholders and an analysis of the existing urban grain and its functional character. The analysis showed that main cultural institutions, diverse shopping possibilities and a combination of sprawled and dense dwelling surround the area, whereas commercial leases are under-represented. Considering the DGNB(UD) criteria and their plea for mixing residential, cultural and commercial functions, the decision was made to emphasize commercial functions by creating a functional three-fold model with leases for one major company (25.000 m^2), a total lease of 12.000 m^2 for small companies, 6000 m^2 for young entrepreneurs, 6000 m^2 for collective housing for entrepreneurs and 6000 m^2 for common facilities like open canteens, meeting facilities, auditoriums and workshops.

Partial Conclusion on the Findings of this Phase

The main issue investigated in the initial phase is whether DGNB(UD) alters the design process compared to how a traditional architectural design process or urban planning process would be laid out.

The early inclusion of stakeholders in the planning of urban areas is present as a demand in Danish legislation already, (By-og Landskabsstyrelsen 2007). The EU standard of Environmental Impact Assessment (EU 1985) also contains criteria concerning social diversity and social economic balance.

Thus, the social diversity of DGNB(UD) criteria 16 *Social and Functional Mix* is already demanded. The municipality and the property developers balance the economy in negotiations, but oftentimes the final financial model is rather a result of prevailing market based circumstances and long-term sustainable financial benefits are not always implemented.

In a Danish context, due to the existing legislation, the DGNB(UD) criteria 16 *Social and Functional Mix* and 38 *Participation* concerning the choice of stakeholders, choice of functions and priority and location of these functions and inclusion of stakeholders in the process, does not cause new design processes differing from existing architectural design processes.

The method of IED in general does not address this design phase and scale, and thus DGNB(UD) conveys new aspects to be taken into account compared to the IED method.

Layout of Site

IED – Different Scale but Same Design Method?

The IED process implicitly presupposes an architectural idea that can be optimized in a series of iterations. (Hansen *et al.* 2005) IED can help prescribe a set out geometry, but it depends on an architectural concept. The geometry approach of the IED method is that of reducing energy consumption for operating the building, and in this phase it would leave out a large part of the many other parameters that an urban scale architectural design process and a DGNB(UD) design process can include. In this sense, IED is not a relevant comparison at this stage.

However developments in software allow that some of the methods of IED can be extended into this phase. The CFD-based software Project Vasari can rapidly link to Google Maps and draw data from the nearest weather station. Very early, rough 3D models can be examined with the simulations tools concerning wind and solar energy (http://labs.autodesk.com/utilities/vasari/). This still does not solve the black-hole-problem of IED meaning that the design process implies an initial design concept as its starting point, even though software development means that even the earliest of urban concepts can be informed and assessed on a technical scientific level.

The DGNB(UD) criteria 3 *Changing Urban Microclimate* includes climatic comfort in the urban spaces of the development plan. This leads to a focus towards wind simulation as a design parameter, and thus the combination of Project Vasari and Autodesk Ecotect was chosen as the digital design tool because it made it possible to link simulations of shadow, solar radiation and wind in a reasonable timeframe for carrying out analyses. Simulating the wind conditions and solar environment on site provided useful information and guidelines for the design in an urban scale. By analysing prevailing wind directions, it was possible to reduce and improve the wind conditions in the areas with the most wind. Simulations were furthermore used to design building masses (overall geometry) in order to guide the prevailing winds around the urban district and not through it (figure 5).

Simulation of solar potential, movement of shadows and the number of sun hours in the urban space were carried out in every phase of the design period in several iterations (figure 4).

By analysing the simulations, it was possible to make evidence based decisions. For instance, the ideal locations of solar panels, material choice, people flow and park design decisions were affected by the simulation results.

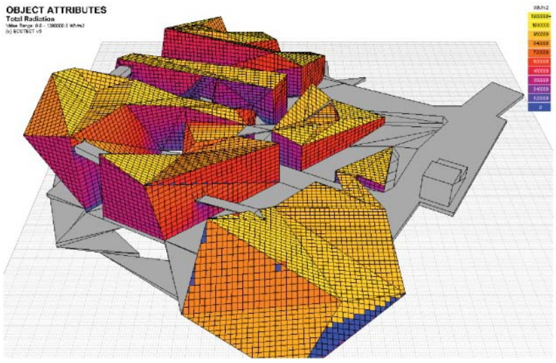

Figure 4. Simulation Results from Ecotect on the Proposed Building Volumes on the Paper Island

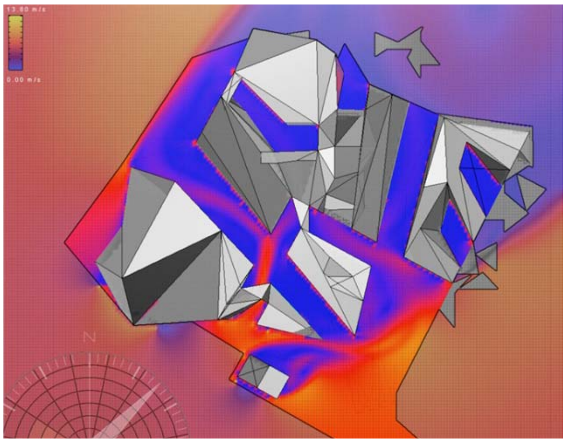

Figure 5. Simulation Results from Vasari of Wind Conditions at the Pedestrian Level Between the Proposed Building Volumes on the Paper Island

Architectural Design Process

To outline a possible effect of DGNB(UD) on the design process, 2 design methods are used: A traditional architectural concept phase and process, and a ‘DGNB(UD)-design process’ where a spread of design solutions for the site and functions were suggested to each DGNB(UD) criteria.

In a traditional architectural design process during the concept phase, the story behind the project, will to a large extent determine the initial work with building geometry. To start the process 3 concepts were developed, that complied with the decisions of the 1 phase. This is following the pattern of a general architectural design process.

The three design concepts each had a different volume concept. One proposal was based on small juxtaposed volumes resembling the scale of a town with streets, squares and alleys (figure 6). One was inspired by a landscape arranging a fragmented building mass in a hilly formation (figure 7). The last proposal was distributed in three major compact building volumes (figure 8).

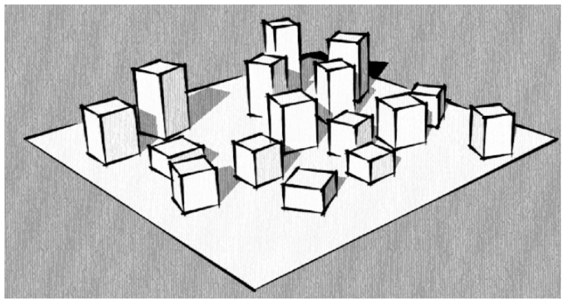

Figure 6. Design Concept 1

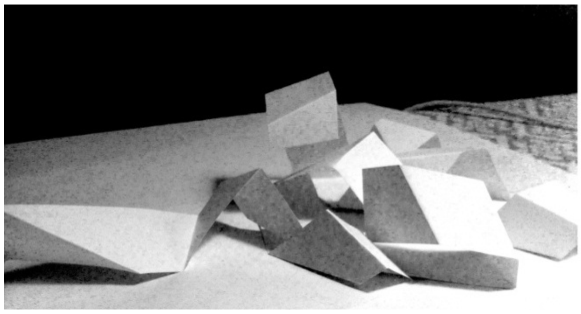

Figure 7. Design Concept 2

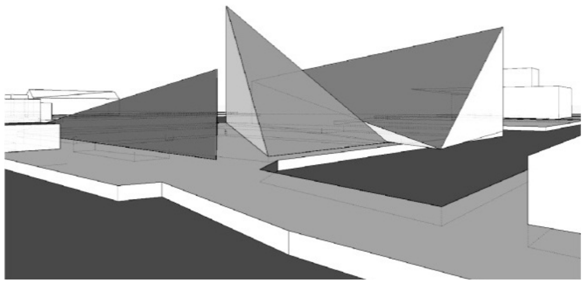

Figure 8. Design Concept 3

DGNB(UD) Design Process

The 3 architectural proposals described above were screened according to 10 strategies, and the best fitted volumetric design concept was chosen to serve as a point of departure for the next stage in this phase (figure 9). The 10 strategies derived from the 45 DGNB(UD) criteria were chosen in the following way.

The first measure that was taken to handle DGNB(UD) as a design tool was to set up a generic framework for the workflow. The process of setting up DGNB(UD) as a design framework presupposed a selection of DGNB(UD) criteria relevant to this phase. All criteria were analysed for their design potential to influence the initial phase and the defining decisions. Each criterion was given a color code resembling their relevance on a scale from green (very relevant) to red (not relevant). Four criteria were ruled not relevant for the design process, six criteria were considered only to have limited relevance for the design process, and 35 criteria were assessed to have major relevance with regards to the layout of the site.

The assessment of the relevance of each criterion was followed by a stage in which the relevant criteria were condensed into 10 interdisciplinary design strategies. This measure was taken out of two considerations: Firstly, the highly detailed criteria and load of content to be considered in the design process had to be made operational with regards to a design process. Secondly, a large part of the criteria were covering the same issues. To avoid a rigid workflow 10 ‘’strategies” were formulated and applied to the design process.

The purpose of the 10 strategies was to comprise a “dramaturgy” for the iterative design process that would lead to a final volumetric design with proposed facade openings, distribution of functions and materials selection. Before commencing the actual design process within the matrix rolled out in the above, the site chosen had to be investigated in order to apply the strategies and thereby implicitly the DGNB(UD) criteria.

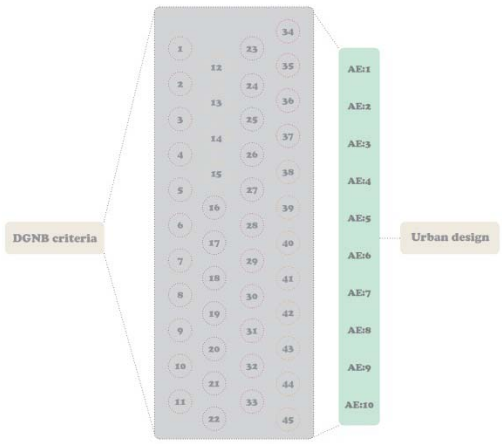

Figure 9. The 45 DGNB(UD) Criteria were Reduced to 10 Interdisciplinary Strategies to make the Criteria Operational

The DGNB(UD) design process was laid out as an iterative process with inspiration from the IED methodology. Quantitative studies (simulations of climatic design parameters like solar radiation, wind conditions and shadow range) informed the relevant DGNB(UD) criteria, were intertwined with qualitative design decisions informed by the specialists engaged in the study. This led to an iterative process in five steps, where the initial architectural design concepts were changed four times due to investigations of the current performance when analysed through the optic of the 10 strategies. The aim was to achieve an optimized building mass that addressed holistic sustainability measures, in both an urban scale as well as a smaller, building specific and user-oriented scale.

Partial Conclusion: Findings from this Phase

In order to be operational in a design process DGNB(UD) has to be reduced in complexity. However, the richness and broadness is one of the major new contributions of DGNB(UD) compared to IED. The question of how to preserve this quality and at the same time make DGNB(UD) operational is not clearly solved in the case. The highlight of 10 criteria was made from site specific considerations and experience with IED and architectural design methods.

Like IED the DGNB(UD) design process has a ‘black-hole-problem’ meaning that the DGNB(UD) criteria cannot create an initial conceptual form. Like IED, the DGNB(UD) process depends on a strike of conceptual thinking which the intuitive architectural design process can handle.

However the initial volumetric distribution of square meters (the priority and location attached to the functions) profited from the systematic approach in DGNB(UD). This meant that the choice between the architectural concepts was based on a deeper and broader level of information. For instance, focus on possible solar energy harvest, urban microclimate of public squares, transportation strategies, social diversity in choice of functions, reuse of existing buildings and biodiversity placed priority on multifunctional features in the concept. The concept that was chosen was the one that was considered to have the largest amount of such multifunctional potential. An example is the green roof that results in a high score in the DGNB(UD) criteria concerned with local handling of rainwater, urban microclimate, biodiversity, public squares and access to green areas. Likewise, the geometry chosen must create both a good urban microclimate (shield public squares for wind), enhance solar energy harvesting and enhance social diversity and activities.

DGNB(UD) does not dictate standard solutions and geometries because so many of the criteria address the relation to site-specific issues that are not exclusively dependent on orientation and climate region. However this singular case study cannot determine if DGNB(UD) in the long run, like IED, will have a tendency to enhance a certain set of standard solution. The focus on multifunctional solutions that will come out well in many criteria might lead to a tendency towards a set of standard solutions, like green roofs with public access.

Methods and software related to those developed for decades in the framework of IED but presently expanded to include wind and solar energy on an urban level create a good starting point for addressing and informing DGNB(UD) criteria concerning urban micro climate and solar energy harvest at a very early design stage. The comfort in urban spaces are much defined by the geometry of the buildings and DGNB(UD) thus actually serves as a remedy to have a holistic approach to design of building volumes and urban spaces as a unit. DGNB(UD) advances decisions concerning buildings to a site-layout phase.

Architectural design methods are still needed to start the design process, but the take-off concerning iterations of technical scientific information can start from a very early stage hereafter because of software like Project Vasari. In this process, DGNB(UD) functions as a systematic way to ensure that a broad, holistic set of parameters are addressed apart from the 2 criteria that Project Vasari can optimize.

The combination of initial architectural design, software like Vasari and the DGNB(UD) criteria will lead to other solutions than would have come from a purely architectural design process or IED process. The keyword for these new design solutions is *multi functionality* understood as design decisions that will result in parallel good assessment in many DGNB(UD) criteria at the same time.

Design of Building Volumes Phase

Architectural Design

The architectural design process in this phase is traditionally about detailing and choice of materials whether it be a choice of glass for windows or surface of walls and facades. The project did not aim at this level. However several of the DGNB(UD) criteria address choice of materials and in this DGNB(UD) proposes something new.

Choice of materials effects several LCA-related DGNB(UD) criteria at the same time. For instance, the urban microclimate is affected by the choice of facade materials. The water handling criteria are affected if the facade materials create toxic downwash. Like in the layout design phase, the design of the building phase will be affected by DGNB(UD) in the sense that focus is on multifunctional solutions that will score well in many criteria at the same time.

The classic architectural design process is organized in a kind of zooming process going from large scale to small scale. This hierarchy of scale is severely challenged by DGNB(UD). DGNB(UD) introduces problems to be considered at an urban level, normally considered on a building detailing level. When reaching the building volume phase, most decisions are already made.

IED

The Design of Building phase is the central area of interest in an IED process. Here, the potential of optimizing the building in regards to energy balance and indoor climate can be realized in a series of iterations. As in the architectural design process, criteria concerning the buildings energy balance are considered in an earlier design stage than normal. DGNB(UD) does not prescribe how the energy consumption of a building can be reduced in an urban design, but singular criteria place emphasis on solar energy harvesting on facades. However, a classic IED process would, in many cases, prove that an excess of solar energy on facades will lead to a cooling demand and thus an increase in energy consumption or an intolerable indoor climate.

DGNB(UD) Design Process

The role of DGNB(UD) in this phase is that of a checklist. It serves to conserve holistic decisions from the previous stages when challenged, for instance, by better indoor climate simulations as described above.

In general DGNB(UD) has outplayed its role when reaching the building phase but implicitly a line of dilemmas and conflicting priorities exist in the transition between urban space and buildings.

Partial Conclusion: Findings for this Phase

The more elaborate design of the actual buildings in the scheme is the classic topic of IED. In IED, various simulations tools are used for optimizing the design in regard to energy and indoor climate. The process of informing the design of the geometry by simulations tools is the classic IED process.

A perspective added to the design process as compared to the IED process is that DGNB(UD) broadens the range of parameters considerably. For example, DGNB(UD)'s LCA-criteria includes the choice of building materials at a much earlier stage. The DGNB(UD) criterion of reuse of existing structures severely affects design solutions concerning LCA and choice of material because embodied energy in existing structures gets a role to play. Nontoxic and low-emission building materials can get a preference by DGNB(UD). Choosing to refurbish existing structures instead of building new ones is also a design that might be promoted by the LCA related criteria.

The holistic approach manifest in the 45 DGNB(UD) criteria draws attention to issues other than energy and the indoor climate of the building, which is the core of the IED methodology. Issues like materials, rainwater management and the distribution of functions are explicitly addressed in the DGNB(UD) design process, thus informing design decisions to a broader extent.

The choice of materials affects the energy and indoor climate calculations conditions. No simulations tools and methods are prescribed for assessing this relationship. In this respect, IED is more elaborate and specific and will thus inform the design decisions more precisely concerning energy and indoor climate conditions. The focus on solar energy on facades would not have been prioritized to this level in IED or an architectural design process.

The DGNB(UD) criteria 8 *Energy-efficient development layout* focuses on solar energy potential. Excessive solar energy on facades can increase the cooling demand and thus have a negative effect on the energy and indoor climate balance of a building, but this is not an issue in any of the DGNB(UD) criteria. In this regard, DGNB(UD) fails to give a holistic perspective on both building and urban spaces, whereas IED reaches further and deeper in this complex problem.

Conclusion

A DGNB(UD) design process introduces a wider range of sustainability issues very early in the design process – earlier than the IED and architectural design methods. However most of the initial inquiries concerning social diversity, choice of functions and inclusion of different stakeholders are addressed in the architectural design method.

Like IED the DGNB(UD) design process is in need of an architectural concept in order for the process to start. Neither can generate an initial layout. The intuitive approach to the initial form is not avoided by using DGNB(UD). However in later design stages, both IED and DGNB(UD) serve as decision making tools and thus as form generators. For example, the DGNB(UD) design method will draw focus towards design solutions that will be assessed well in a multitude of criteria. Only a limited set of solutions have this potential. There might be a potential risk or opportunity that a DGNB(UD) design process will lead to standard solutions, such as green roofs.

DGNB(UD) challenges an architectural design method by questioning the classic 'zooming' in scales. For example, the focus on LCA of materials when designing on an urban level provokes new approaches.

IED has developed over several decades, and the software industry has continuously facilitated with software for different sorts of iterations at different levels in the design process. In DGNB(UD), this is not the case. Certain areas such as climate comfort in urban spaces and the energy potential on facades can be addressed by software such as Project Vasari (wind and solar energy). For example, the work with LCA of materials on an urban level is not facilitated by software.

The relationship between choice of geometry and choice of materials are well developed on a building design level (classic IED subject), but the connection to decisions on an urban level is not facilitated by software. For example, the risk of high indoor temperature due to excessive solar energy harvesting is not addressed.

The interface between the DGNB(UD) and the building scale (DGNB building) calls for further investigation if the DGNB should function as a design tool.

IED is very operational today after 2 decades of continuously advancement in facilitating software on a building level. However, IED is limited in the number of parameters that are varied in the design process which makes it operational. Using DGNB(UD) as a framework for design implies a step into a much broader realm of a multitude of parameters where the majority are not yet facilitated by adequate software. Therefore, it is necessary to narrow the criteria down in order to make it operational in a design process. In the case examined in this paper, a generic reduction or hierarchy was not obtained. The 10 criteria derived from the 45 were to a large extent site and project specific.

Discussion: Mapping of a Holistic Sustainability Design Process

It took 2 decades to make IED truly operational with a span of software development on the side track and a slow transformation of the building industry and design practice. DGNB(UD) introduces a wide range of criteria early in the design process, but the assessment of the design solutions for each criteria is not based on simulations or calculations. This makes the DGNB(UD) design process less objective than IED and the results more speculative. The question is why DGNB(UD) does not present simulations tools along with the criteria? For instance VISSIM (Vissim web) is a simulation tool that would give the assessment of the traffic related criteria considerably more substance. Concerning the management of rainwater, software that simulates the flow of water from different categories of rain exists. The same goes for LCA. In regard to a fast running design process, simulations also have an advantage because they can give information at the right pace and level. The research in the context of IED provides knowledge of how to use different simulation tools in different stages of the design process which could be transferred to DGNB(UD). In this respect, DGNB(UD) is a checklist that has the potential of developing into an intelligent design system. This could create the leap in information level that is needed.

The question of making a very rich and complex system operational in a design process without losing the complexity calls for further investigations. The lack of hierarchy in DGNB(UD) is carefully constructed together with the choice of criteria and assessment methods. However in a design process hierarchies are central.

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Conceptual Design of a Housing Project Based on Axiomatic Design

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Abstract: The complexity of architectural design is steadily increasing due to the need for designers to address environmental and energy issues along with social-economic considerations. Recently, additional parameters have to be considered during the early phase of the design process, and this has resulted in a conceptual design phase that is becoming more challenging. In this phase, architects have the greatest opportunity for addressing the complexity of design and influencing project outcomes. Usually, during the early phase of the design process, architects use previous experiences and knowledge for defining a simplified problem in order to stimulate the early conjecture of possible solutions. Therefore, the design problem and related solutions are constantly reformulated co-evolving together during the design process until the relevant issues of the specific task and the related design solution are defined. Unfortunately, a designer's knowledge and experience are often insufficient due to the increasing complexity of architectural design today. A means for addressing complexity in design problems consists of dividing a design problem into simpler sub-problems by decomposition, and several approaches for decomposition of design problems are available. Contrary to conventional decomposition, the decomposition by Axiomatic Design (AD) is performed shuttling to-and-from problem and solution and decomposing each into a hierarchy in a systematic manner supported by basic principles of analysis and decision-making. Due to the simultaneous evolution of the architectural concept design, AD decomposition is applied to a successful architecture to investigate its contribution to the improvement of the manageability of design complexity in conceptual design generation. This study intends to contribute to the future development of decision-making and knowledge integration support for understanding and achieving architectural design concepts in an efficient and effective way.

Keywords: Architecture**,** Axiomatic Design, Conceptual Design.

Introduction

The complexity of architectural design is increasing in an exponential way: architectural planning has to harmonize various demands in a utilitarian and aesthetic way within the given socio-economic constraints. Architectural design has to provide a product that satisfies the specific needs of market segments, but at the same time it must be produced efficiently (Sabbadin 2011). Moreover the traditional decision model based on a balance among quality, time and cost has widened, involving sustainability. Therefore the solution has to be optimized with respect to a large number of different (sometimes conflicting) requirements and constraints, and it has to be selected from different available alternatives.

Especially in the early stage of the design process, designers have the greatest opportunity to influence the project outcome. In this stage, decisive design decisions regarding performances, appearance and costs are made. In contrast, decisions made in the later stages have a minimal influence on the project outcome, and they do not correct poor decisions made initially (American Institute of Architects 2007).

In the initial stage, architects usually define a simplified problem, and they elaborate a conjecture of possible solutions in order to obtain more information about the problem from the client. Therefore, they do not start with a full and explicit definition of the design problem because it requires a considerable amount of knowledge and experience from a wide range of disciplines and stakeholders. Instead, they search for a way to limit the potential solutions to a manageable group. To do this, they select a small set of objectives, usually depending on their subjective judgment, previous experiences and knowledge (Darke 1979). Therefore, usually the design problem escapes an initial complete description found in scientific problems (Lawson 1994). As a result, architects constantly need to reformulate the design problem and the relative solution, while they keep track of all relevant issues of the design task (Darke 1979). In this process, the design problem and solution co-evolve together following spiral and cyclic stages (Roozenburg and Cross 1991). This approach emphasizes intuition and experience, but this is often not adequate, when the desired solution is not easily found, when the cost of failure is high, when the design task is complicated, or when multiple stakeholders are involved in the process. Experience should be supported by systematic approaches to design in order to generate effective solutions that meet the required needs. These approaches, developed in engineering design, propose systematic procedures to support design activities focusing on the analysis of the problem and externalizing design thinking (Cross 2000).

AD, one of these design approaches, is distinguished from other systematic design methods by having design axioms that guide the decision-making activity, especially in the early design phase, towards good design decisions. Moreover in AD, the formulation of the problem and ideas for a solution evolve together with constant shuttling to-and-from problem and solution in a top-down manner (Suh 1990). Also, in the architectural design process, problem specification and solution are developed together during an incremental and cyclic process, but the decision-making activity is performed by intuition and experience. Therefore AD may provide a suitable systematic approach for architectural design in the conceptual phase to perform decision-making and knowledge integration in complex design problems.

In this study, the conceptual design of a successful architecture is decomposed according to AD. Decomposition is the means of addressing complexity in a design problem by dividing a design problem into simpler sub-problems. Several approaches for the decomposition of design problems are available. Contrary to conventional decomposition, the AD decomposition is performed, shuttling to-and-from problem and solution, moving down and decomposing everything in a systematic manner into a hierarchy. There are several possible ways to decompose a problem. In this analysis, the decomposition is conducted according to the user-centered prospective (Norman 1988): the mapping process of requirements concerns the user needs.

This analysis focuses on AD decomposition to evaluate the contribution of decomposition for the improvement of the manageability of design complexity in the conceptual design phase. This study intends to contribute to the future development of a decision-making and knowledge integration support system for the understanding and achievement of architectural design concepts in an efficient and effective way.

Axiomatic Design

AD is a design theory developed by Nam P. Suh beginning in the 1970s at MIT in the field of mechanical engineering. This approach proposes a framework to help the design development of products, systems, and processes through a rational and systematic approach. AD supports the development of solutions to design problems through basic principles of analysis and decision-making (Suh, 1990). AD states that all good design decisions, whether they are for products, systems or processes, involve the same principles. These principles guide the decision-making activity in the design process and provide criteria to evaluate the synthesized idea before and during the analytical phase, or to select the most appropriate solution from several plausible designs within a set of constrains (Suh 1990). It has been shown that this design theory can be applied to many different fields of design problems (Kulak *et al.* 2010).

In AD, the design world is composed of design domains. The design domains represent four different kinds of design activities (figure 1) (Suh 2001):

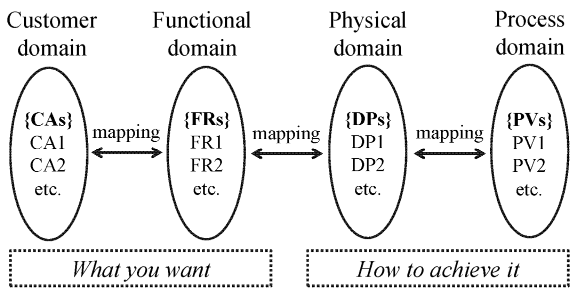

Figure 1. Design Domains

- The customer domain is characterized by customer attributes (CAs). CAs are customer needs or attributes that the customer is looking for in a product or process or system.
- The functional domain is characterized by functional requirements (FRs) and constraints (Cs). FRs are a minimum set of independent specifications that satisfy the customer needs. Cs are bounds of acceptable design solutions.
- The physical domain is characterized by design parameters (DPs). DPs are physical variables that characterize the design, and satisfy the specified FRs.
- The process domain is characterized by process variables (PVs). PVs are variables concerning specified attributes that characterized the process.

According to Suh, design is the creation of synthesized solutions that satisfy perceived needs through mapping process. It consists of the interplay of “what we want to achieve” and “how we want to achieve it” (Suh 2001). AD guides designers through the interplay (mapping) between the domains: from

CAs into FRs, then from these into DPs, and finally from these to PVs. This approach begins with a clear description of the design goals: at the beginning, designers define the perceived needs that the customer is looking for in a product. These attributes must be translated to a minimum set of FRs and to Cs. Cs are defined in order to determine the bounds of an acceptable design solution. Then, designers must conceptualize a solution by mapping: they go from the functional domain to the physical domain, and they must elaborate a solution expressed in terms of DPs that satisfies the established FRs. Later in the process domain, the solution specified in term of DPs is defined according to PVs for production (Suh 2001). During this process, the designers transform the design intent into a detailed design through the decomposition. The decomposition is performed by zigzagging breaking down FRs, DPs and PVs into a hierarchy. It consists of a mapping that goes from the domain on the left to the domain on the right and in coming back to the domain on the left. In this domain, a lower level is generated, and the process is pursued until the design is completed.

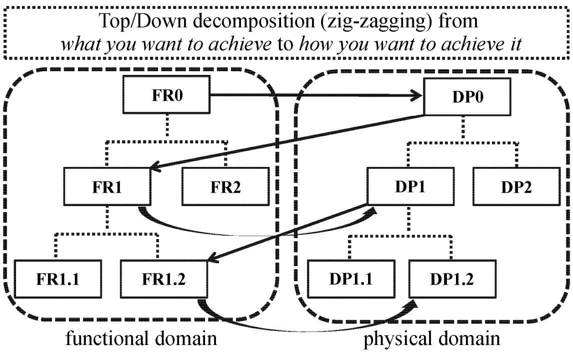

Figure 2. Zigzagging between FRs and DPs

In figure 2, the decomposition between FRs and DPs is illustrated: designers go from the FRs in the functional domain to the physical domain conceptualizing a design in terms of DPs. Then they come back to the functional domain, and create a detailed lower level of FRs that collectively satisfies the highest level.

At each level of decomposition, the design decision must be consistent with all higher level design decisions that were already made. The right decisions are made using the Independence Axiom. When several design solutions that satisfy the Independence Axiom are available, the Information Axiom can be used to select the most appropriate alternative from several plausible designs within a set of criteria in the shortest time (Suh 1990). The design process ends with a clear description of the design solution (Suh 1990).

In AD, there are two design axioms that guide the decision-making activity:

- Axiom 1 - Independence Axiom: maintain the independence of the FRs;
- Axiom 2 - Information Axiom: minimize the information content of the design (Suh 1990).

In order to be sure that the right decisions are made at each level of decomposition, the design equation must be elaborated. At each level of the design hierarchy, the set of FRs and the set of DPs can be expressed mathematically in terms of vectors. The mapping process between FRs vector and DPs vector can be written as:

$$\{FR\} = [A]\{DP\} \tag{1}$$

where [A] is the design matrix; {FR} is the FRs vector; {DP} is the DPs vector (Suh 2001). An equation composed by three FRs and three DPs may be written in terms of elements as:

$$\begin{aligned} FR1 &= A11\ DP1 + A12\ DP2 + A13\ DP3 \\ FR2 &= A21\ DP1 + A22\ DP2 + A23\ DP3 \\ FR3 &= A31\ DP1 + A32\ DP2 + A33\ DP3 \end{aligned}$$

The related design matrix is written in the following form:

$$[A] = \begin{bmatrix} A11 & A12 & A13 \\ A21 & A22 & A23 \\ A31 & A32 & A33 \end{bmatrix} \tag{2}$$

In regard to the design matrix, designs can be separated in three groups (Suh 1990):

- Uncoupled designs: each FR is satisfied independently by its related DP, and thus Axiom 1 is satisfied. The resulting design matrix is diagonal:

$$[A] = \begin{bmatrix} A11 & 0 & 0 \\ 0 & A22 & 0 \\ 0 & 0 & A33 \end{bmatrix} \tag{3}$$

- Decoupled designs: the independence of the FRs can only be guaranteed if the DPs are solved in a particular sequence. The resulting design matrix is triangular, and all upper triangular elements are equal to zero:

$$[A] = \begin{bmatrix} A11 & 0 & 0 \\ A21 & A22 & 0 \\ A31 & A32 & A33 \end{bmatrix} \tag{4}$$

- Coupled designs: a FR is influenced by more than one DP simultaneously, and thus Axiom 1 is violated. In this design, the related design matrix has no special structure.

In order to satisfy the Independence Axiom, the design matrix has to be diagonal (*uncoupled*) or at least triangular (*decoupled*). Otherwise the design matrix is *coupled*. In this case, the design solution has to be changed, and the mapping process between the domains has to be restated until the Independence Axiom is satisfied (Suh 1990). The realization of uncoupled designs is rarely possible in real life, while coupled or decoupled designs are the most frequent, especially in complex structures (Durmusoglu and Kulak 2008).

Conceptual Design Decomposition of a Case Study using AD

This analysis intends to evaluate the contribution of AD decomposition for the manageability improvement of design complexity in the conceptual design phase. Decomposition is a method for addressing the complexity of the design problem by dividing a problem into simpler sub-problems. Contrary to conventional decomposition, the decomposition by AD is performed, shuttling to-and-from problem and solution, moving down and decomposing everything into a hierarchy. This process has similarities with the design process usually performed by the architect in which design problem and solution co-evolve together during the process (Roozenburg and Cross 1991).

In AD decomposition, the design decisions are made in an explicit way in order to evaluate the solution using the design axioms. These general principles guide the designer in the decision-making activity to eliminate bad ideas as early as possible and to concentrate on promising ideas. In particular, the Independence Axiom supports the designer to define design solutions that independently satisfy the defined FRs, removing problem of conflicts and interactions managing (Mullens *et al*. 2005). Conflicts and interactions between requirements must be recognized and managed early in the design process in order to reduce the design complexity and guarantee a successful design (Withney 1990). In architectural design, design decisions are usually performed by intuition and experience, but this approach is not often adequate for managing the complexity of an architectural design problem.

In order to address complexity of architectural design, the AD decomposition is tested. In this analysis, the design problem and related concept solution are decomposed into several simpler sub-problems and related sub-solutions. Several possible ways may be applied to decompose a design problem, such as functional decomposition or decomposition by sequence of user actions. In this case, the decomposition is defined according to a user-centered prospective based on the needs of the user (Norman 1988), including aesthetic issues. The conceptual design generation is reviewed and externalized, starting with an explicit statement of the design goals (“what the architect wanted to achieve”). The realized design solution is decomposed and analyzed in terms of physical attributes (“how the architect achieved it”) which satisfy the defined design goals. Therefore, the design problem and the realized design solution are broken down coherently in a systemic way transforming the design intent into the realized concept design solution through the process of mapping, zigzagging and decomposition.

In this case analysis, the check of the Independence Axiom by the design matrixes is not discussed since the analyzed case is a successful design project, and therefore the design matrixes do not entail significant observations.

Case Study Description

The selected case study is a housing development, the Fredensborg Housing, designed by Jørn Utzon in Fredensborg (Denmark) in the 1960s. In 1962, Jørn Utzon was commissioned to design a housing scheme for Danish citizens who returned to Denmark after having worked for longer periods abroad. This development is intended for retired older people (Faber 1991). It consists of forty-seven courtyard houses (A) laid on the natural terrain slope and thirty smaller terraced houses (B); all are grouped around and linked to a community center (C) that provides communal facilities (fireside lounge, dining room, central courtyard, library, office and guestrooms) (Mogens 2004) (figure 3).

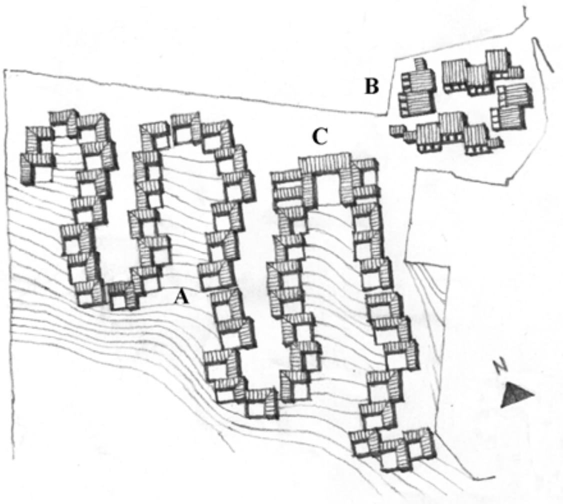

Figure 3. Fredensborg Housing, arch. J. Utzon, 1962-1965, Fredensborg (Denmark)

The courtyard houses are placed along four roads to form rows of houses overlooking both the road and the common green area. Each courtyard house consists of an L-shaped building on two sides and walls on the two opposite sides that define a private garden. This house is composed of two wings, one for living and the other for sleeping and a courtyard. The L-shaped houses have the same kitchen and bath core, but Utzon created different types of units, both in plan and in size, using the same configuration. The courtyard house types are simple with well-functioning plans that offer a wide variety of activities within a common framework (Møller and Vibe 2006). All the living rooms are oriented toward the south or west, and the small garden courts are surrounded by wall. The height of walls was individually determined according to the sun orientation, wind directions and both inner and outer views in order to guarantee privacy, shade, view and enclosure (Faber 1991). The community center is located in a central position of the housing development, and it is designed as a three-winged courtyard building with an opening to the south. A separate cluster of terraced houses is located in the north-eastern corner of the development. It consists of one-and-a-half storey townhouses grouped around an inner square (Mogens 2004).

The Fredensborg Housing is considered a successful architectural design, and the value of the work was recognized by official awards. Utzon won the Pritzker Architecture Prize widely considered the Nobel Prize of architecture in 2003, and his housing project was mentioned by the jury for overall architectural quality. The factors considered by the Pritzker Architecture Prize for the evaluation were: commodity, firmness and delight. The jure wrote about Utzon's work: "his housing is designed to provide not only privacy for its inhabitants, but pleasant views of the landscape and flexibility for individual pursuits - in short, designed with people in mind" (Pritzker Architecture Prize Jury 2003).

The concept of the value of architecture considered by the Pritzker Architecture Prize has an ancient origin. Marcus Vitruvius Pollio, a Roman writer, architect and engineer of the 1st century BC, asserted that good architecture must exhibit the three qualities of firmitas (firmness*)*, utilitas (usefulness*)* and venustas (pleasantness*)* (Vitruvius 1960). Therefore a work of architecture is characterized by the suitability for the use by human beings and its adaptability to specific activities (usefulness), the stability and the permanence of the construction in relation with the environment (firmness) and the aesthetic aspect through architectural expression (pleasantness). These aspects cannot be separated, but the relative importance given to each can vary (Ackerman 2013). This concept of the architectural value persists nowadays with slight variation on the triad sequence or new concepts (Collins 2013).

Usefulness is concerned with space, access and flexibility. A design solution defines different kinds of space according to different uses; it specifies the access to these spaces and the circulation among them, and it must provide adaptable spaces for different users (Ackerman 2013). The planning of space entails the arrangement and the quality of space (space allowance and attributes), and it varies according to the type of architecture, the cultural requirements, the user habits and activities and the required furniture and equipment. The planning of access intends to simplify the circulation of persons and things among differentiated spaces and the connection between inside and outside. The planning of flexibility establishes the usefulness of the space for all, the adaptability to different functions or users and the ease of management (Ackerman 2013).

Firmness is concerned with the structural stability, health and safety aspects, the comfort and the durability of systems, finishes and fittings. The architect must guarantee the stability, foreseeing the effects of destructive potentialities, and the durability, assuring the permanence of stable and comfortable conditions. The choice of materials and techniques depends on their capability to create stable structures and to withstand the environment for a long time. Moreover the planning must adjust the varying behavior of the natural environment according to the unvarying physical needs of human beings. In order to make buildings habitable and comfortable, the architect must control the indoor effects of the climate conditions (sun, wind, rain) and external factors (noise, smog) and of the surrounding environment (trees, land formations, other buildings) (Ackerman 2013).

Pleasantness refers to the ability to create a sense of place through the composition of architectural forms. It involves aspects of the relation with the physical surrounding (White *et al.* 2004). The basic elements of architectural form are space and mass. Form in architecture consists of the composition of mass and space in an ordered form and in the communication of specific meanings conferred by adopted buildings techniques. The quality of space and mass is given from proportion, light, texture and color (Ackerman 2013). Moreover the architecture may be integrated with the natural and architectural surrounding in order to create harmonies with the context and the pre-existing elements (Ackerman 2013).

Conceptual Design Decomposition

The decomposition of the case study starts with the specification of the design intent in the first level. The understanding of the user's needs must be expressed in a minimum set of FRs that satisfies the defined needs. The first level of FRs in the functional domain is defined, and results in the following:

FR = Realize a housing development for returning elderly citizens from abroad

After the FR is established, a design is conceptualized in the physical domain and the related DP that satisfies the established FR is defined through the mapping process between functional and physical domains. The DP in the physical domain is defined, and results in the following:

DP = A housing project

Then the designer must come back to the functional domain, and divide the FR into a more detailed lower-level of FRs that satisfies the highest level collectively. At each level of the decomposition, the detailed lower level design decisions must be consistent with the higher level design decisions that were already made (Suh 2001). Moreover only a minimum set of independent requirements must be identified that completely satisfies the highest level of FRs. In the analyzed case, the lower level of FRs is determined according to the Pritzker Architecture Prize's criteria and to Utzon's thinking. Utzon asserts that the architect experiments with his shape-creating expertise practicing with scales (proportions), with mass and with rhythms formed by masses grouped together, by color combinations, by light and by shade. This expertise requires close familiarity with materials and understanding of their structure, weight and hardness in order to be able to fashion and use them in accordance with their constitution. A desire for well-being must be fundamental to all architecture. It requires an ability to create harmony from all the demands made by the undertaking, the ability to meld them to form a new whole (Utzon 1948). Therefore the second level of FRs is defined as follows:

FR1 = Provide spaces for living
FR2 = Provide conditions for living

Regarding pleasantness, aesthetic aspects are not functional requirements; therefore this category is defined "non-functional requirements" (nFRs) (Thompson 2013). Non-functional requirements indicate how the design should be, and specify the attributes that the artifact should have. They are more similar to constraints that to FRs. For each nFR, it is rarely the translation to a single physical feature. Therefore the mapping process is not applied to nFRs (Thompson 2013). In this case study, the related nFR is defined as follows:

nFR1 = Be beautiful

In order to define when the design solution is acceptable, constraints (Cs) must be specified in the functional domain. Cs set limit on the values of a quality or metric (Thompson 2013), and define bounds of acceptable design solutions. They differ from FRs since they do not have to be independent. In this case study, a constraint is cost (C1). The design is acceptable if the cost of the solution does not exceed the established limit (Suh 2001). In the analysed case study, the forecasted cost budget was too low, and the construction site was interrupted until extra money was provided. Instead of modifying the design solution, the cost limit was corrected in order to guarantee that the design solution maintained the expected quality (Faber 1991). Cs such as urban and building regulations, resources, time, whole-life value are not considered in this analysis.

The DPs that satisfy the defined set of FRs are:

DP1 = Spaces for living
DP2 = Building body

Relative to DP1, the design solution consists of a low-density housing with private gardens, common open spaces and community spaces. Details of the design solution regarding each area consist of:

- Courtyard houses area (A): single-family houses with private courtyards and direct access to the common green area
- Terraced houses area (B): terraced houses with small enclosed gardens and direct access to a common inner square
- Community center area (C): community spaces (living and dining rooms with administration office, library and guestrooms) in a central position of the development (Faber 1991)

Regarding DP2, the solution provides well-oriented, wind-protected and insulated buildings; moreover durable building techniques and materials are applied. Details of the design solution regarding each area consist of:

- Courtyard houses area (A): south, south-west and south-east oriented single-family houses, and south-oriented and wind-protected courtyards
- Terraced houses area (B): south or west-orientated terraced houses, and south or west-oriented and wind-protected enclosed gardens
- Community center area (C): south-oriented plateau protected by three linked buildings, with an opening to the south (Mogens 2004)

In regard to nFR1, the design solution satisfies this requirement carrying out a balance between repetition and variety of buildings form and between the built and natural environment. Details of the design solution regarding each area consist of:

- Courtyard houses area (A): four different types of courtyard house and alternation of buildings, enclosed gardens and open spaces
- Terraced houses area (B): alternation of enclosed gardens, buildings and open spaces
- Community center area (C): a courtyard building opened towards the common green area

In the third level, FR1 and FR2 are decomposed. FR1 is divided into four FRs, and two nFRs are defined. They are described as follows:

FR1.1 = Provide access and connections
FR1.2 = Provide spaces for private and community

living activities
FR1.3 = Provide spaces for service activities
FR1.4 = Provide spaces for building systems

nFR2 = Be usable by different users
nFR3 = Be comfortable

The related DPs that satisfy the FRs listed above are:

DP1.1 = Access and circulation spaces
DP1.2 = Private and community living spaces
DP1.3 = Service spaces
DP1.4 = Building systems spaces

In regard to DP1.1, the solution provides access to the entrance hall of each building from a common open space (road or square) through any sheltered area. The entrance hall is connected with the service and the living areas. The living area is related to an enclosed garden. The bedroom area is a secluded portion. Details of the design solution regarding each area consist of:

- Courtyard houses area (A): the courtyard houses are serviced by cul-de-sac roads. The access takes place from the road through a protected open space to the entrance hall. The entrance hall is connected with the kitchen, the living area, the courtyard and the sleeping area. The living room is directly connected with the courtyard.
- Terraced houses area (B): the terraced houses are serviced by a common square or a service road. The access take place from the square directly or from the road through a protected open space. The entrance hall is connected with the living area and the services. The living room is directly related to the enclosed garden and an upper level sleeping area.
- Community center area (C): the community center is serviced by a road. The access takes place from the road through a protected open space. The entrance hall is connected with services (kitchen, cloak room, toilet) and the lounge area. The lounge area is connected with the dining area, the courtyard and the guestrooms. The guestroom area has also an independent entrance from the road.

Relative to DP1.2 and DP1.3, the realized solution gives the possibility for its inhabitants to be completely isolated and independent for any activities, inside the courtyard, and, at the same time, to participate in the community life when they want it (Mogens 2004).

The arrangement of each house consists of a living area with enclosed garden and a small workshop or studio, a sleeping area, kitchen and bathroom core. The community center has a similar arrangement: living area with open space, services area and sleeping area (with own garden). Details of the design solution regarding each area consist of:

- Courtyard houses area (A): the courtyard houses have a living room with an outside multi-use courtyard, a small workshop or studio, a kitchen-bathroom core and an eventually garage or lumber room. The sleeping area has one bedroom and one other room or two other rooms.
- Terraced houses area (B): the terraced houses, planned for an individual, have a living room with a study area and a small enclosed garden, a kitchen-bathroom core and a bedroom.
- Community center area (C): the community center has a living area with an isolated dining room, a common courtyard and a related kitchen-bathrooms area. Guest rooms are provided with own enclosed gardens.

Relative to DP1.4, a boiler space in the community center basement is provided that is connected with all houses by a service channel (Mogens 2004).

In regard to nFR2, the realized solution provides different size and configuration types of courtyard houses for different demands and adaptable spaces (especially the related outside area) to the variable user needs. Details of the design solution regarding each area consist of:

- Courtyard houses area (A): the courtyard houses, otherwise using the same scheme, consist of four size and configuration types (one or two bedroom, with or without garage) with a multi-activity adaptable courtyard.
- Terraced houses area (B): the terraced houses consist of only one size and configuration type because they are each intended to accommodate an individual. Their outdoor areas have fewer possibilities for adaptation than the courtyard house gardens.
- Community center area (C): the community center provides an adaptable living area and terrace for different common activities (parties, concerts, lectures) (Faber 1991).

Relative to nFR3, the realized solution guarantees high thermal and air-flow comfort spaces providing south-orientated and wind-protected buildings and enclosed gardens. Regarding daylight comfort, well-oriented openings are arranged. Acoustic comfort is provided by locating the sleeping areas in enclosed portions. Details of the design solution regarding each area consist of:

- Courtyard houses area (A): the house entrances are toward north or east or west; the houses have the living room facing south or west with wide adjustable openings for natural lighting. The height of the courtyard walls varies individually according to the sun orientation and the wind direction.
- Terraced houses area (B): the house entrances are

toward north or west; the living room faces south or west side with wide adjustable openings for the daylight comfort.

- Community center area (C): the community center is designed as a three-winged courtyard building with an opening to the south and the entrance on the north side. Wide adjustable openings for natural lighting are provided in the living and dining areas.

FR2 is decomposed in five sections, and two nFRs are defined. They are described as follows:

FR2.1 = Separate inside from outside
FR2.2 = Divide interior spaces
FR2.3 = Provide supplies for living
FR2.4 = Provide support for living
FR2.5 = Support loads

nFR4 = Be efficient regarding comfort
nFR5 = Be durable

The related DPs that satisfy the FRs listed above are:

DP2.1 = Building shell
DP2.2 = Interior walls
DP2.3 = Building systems
DP2.4 = Furniture
DP2.5 = Supporting structure

Regarding DP2.1 according to nFR4, the realized building shell delimits the spaces guaranteeing thermal comfort by thermal insulated techniques. Acoustic insulation is provided in the sleeping areas.

Moreover relative to nFR5, the building shell is realized using durable materials (bricks in walls, tiles in roofs and wall coverings and clinker in external pavements) and enduring technical solutions.

Relative to DP2.3, a centralized heating system is supplied that connects a boiler in the community center basement with all houses (Mogens 2004).

In regard to DP2.5, the solution consists of a masonry load-bearing structure.

nFR1 is decomposed in two specific aspects as follows:

nFR1.1= Be varied
nFR1.2= Be integrated in the physical surrounding

In order to satisfy nFR1.1, the design solution proposes formal variations on a repetitive scheme. The displacement of the buildings sets up spaces of varying sizes. The buildings have cubic forms with numerous variations due to the specific designing of the courtyard walls. Each courtyard differs in a harmonious arrangement in order to realize both enclosure and the best view from each individual garden (Mogens 2004). The general cohesion of housing is realized by use of a repetitive scheme and similar material colours of the surfaces (yellow tiled roofs, brick walls and clinker external surfaces) (Weston 2002).

Relative to nFR1.2, the design solution provides contextual integration of the housing development with the surroundings through the variety of open spaces (access roads, courtyards and open green area) and through a gradual transition from the open green area to the enclosed gardens.

Discussion

The purpose of this study is applying the AD decomposition to an architectural case study to evaluate its usefulness for addressing the complexity of the design problem in architecture in the conceptual design phase. Moreover it might enhance the consistency of a concept design solution according to defined design goals in the early phase of the design process.

Due to the similarity between the AD decomposition and the architectural approach to design regarding the co-evolution of problem and solution, AD is applied to analyze the conceptual design of a successful architectural design project according to a well-established concept of quality in architecture. Through the process of mapping, zigzagging, and decomposition, the design problem is decomposed progressively according to a user-centered prospective and the related design solution is analyzed in a systematic manner, evaluating the consistency of the developed design solution compared to the defined design intents.

In AD decomposition, the use of the Independence Axiom encourages the development of solutions that satisfy independently the defined FRs, removing the problem of managing conflicts and interactions. In this study, the analysis of the Independence Axiom by the design matrixes is left out since it is not significant in the case of a successful design project. Future analysis could evaluate the management of conflicts and interactions between FRs in order to reduce design complexity since the conceptual design phase and consequently to improve the effectiveness of the design solutions.

Conclusions

In a context in which the elements and metrics of building performance are undergoing global transformation, the architectural profession would benefit from a clear method for addressing the complexity of the design problem as well as a decomposition approach for improving the manageability of design complexity. Energy efficiency, life cycle assessment, green materials and sustainable design are a sampling of the relatively new requirements for architecture.

This analysis of the conceptual design process of a successful architecture intends to establish the basis for the application of the decomposition process using AD in the conceptual design generation of architecture in order to adequately manage and address the architectural design complexity since the early phase of the design process. The mapping process of requirements will be conducted considering all stakeholders involved in the building design process. Further study would explore the ways to recognize and manage conflicts in the earliest stages of the design process. Based on these analyses, a decision-making and knowledge integration support framework could be developed to provide more effective concept design solutions in a more effective manner.

This paper has proposed this method for the purpose of analyzing a completed and well regarded piece of architecture. Further work is needed to discover the benefits and difficulties inherent in AD in the context of a new design project, especially during the earliest stages of the design process.

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Structural Design of an Affordable, Functional, Sustainable Solar Decathlon House

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Abstract: Worcester Polytechnic Institute is competing in the Solar Decathlon China 2013 competition with Polytechnic Institute of New York University and Ghent University. The competition requires teams to design net-zero energy houses that are cost-efficient, structurally sound, and visually appealing. This paper summarizes the structural design of the house in a multi-disciplinary context. The structural system was selected to respond to various architectural, construction and sustainability goals in addition to providing good structural performance. The design aimed to create an insulated, lightweight, modular, and aesthetic solution that is constructible, and re-constructible. The main structural component of the house was fiber reinforced sandwich panels. This unconventional material challenged the structural design team to prove the efficiency of the panels through structural and fire testing and modeling. This paper introduces the structural design and construction of the solar decathlon house, and discusses design delivery process of the multi-disciplinary, multi-national team.

Keywords: Solar Decathlon China, Fiber Reinforced Sandwich Panels, Structural Design, Multi-Disciplinary Design, Sustainability.

Introduction

Solar Decathlon China

The United States Department of Energy has organized the Solar Decathlon competition periodically since 2002. This is the first time that the competition is held in Asia/China and co-sponsored by the China National Energy Administration. The competition requires participating teams to design, build and operate energy efficient, affordable and appealing houses (United States Department of Energy 2013). The goal of the program is to create awareness of clean energy design solutions and provide students with hands on training for affordable, functional, energy efficient design. This year, the competition was hosted by the city of Datong, China, from July 17-August 13.

Multi-Disciplinary, Global Design Team

Worcester Polytechnic Institute (WPI), Polytechnic Institute of New York University (NYU Poly), and Ghent University formed a design team to compete in the Solar Decathlon China 2013 (BEMANY 2013). The team, called BEMANY – short for Belgium, Massachusetts and New York- is composed of over 40 students and faculty members in architectural engineering, architecture, civil and environmental engineering and other engineering, science and communications. The house designed by team BEMANY is called Solatrium (Solatrium 2013). Solatrium uses a unique structural system that was selected to fulfill both structural and non-structural goals of the project.

This paper introduces the structural design of the Solatrium. The structural system is mainly composed of fiber reinforced polymer sandwich panels and pultruded shapes. This system was selected due to its higher strength to weight ratio meaning larger sized panels, the ability to modularize the construction, the ability to allow for de-construction and re-construction, and the ability to incorporate thermal insulation within the structural system. This paper introduces the design and construction of the structural system of the Solatrium as part of a larger multi-disciplinary, multi-cultural team process. The educational aspects of the project from the students' perspective are also mentioned.

Team BEMANY Entry: The Solatrium

The Solatrium is so named by the use of a central atrium held in place by a truss with windows enclosing the atrium. The architectural rendering of the Solatrium is shown in figure 1. The floor to ceiling windows and open central atrium emphasize direct solar gain and create a strong visual connection to the outdoors.

Figure 1. Architectural Rendering of the Solatrium

The floor plan of the Solatrium, shown in figure 2 is an 11.25m x 11.25m square centered around a raised atrium with a protruding carport extending from the structure. The floor plan of the Solatrium contains few interior walls in the living space of the home. This and the prevalence of natural light create an open environment for the inhabitants. The finished usable area excluding the mechanical room, kitchen cabinets, and the atrium is 99 m^2.

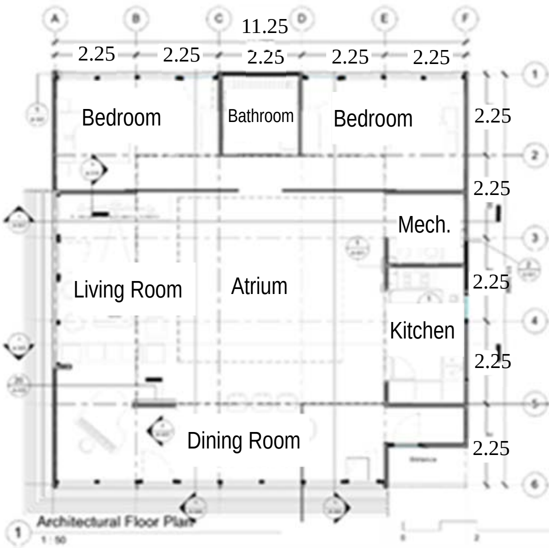

Figure 2. Architectural Floor Plan (dimensions in m)

A unique design challenge was to create a house that can be built in the United States, deconstructed and shipped to China to be re-constructed for the competition. The Solatrium is the only competition house that is entirely made in the US.

Structural System Selection

The structural system was selected as a result of a decision making process which considered the following goals:

- Span large openings demanded by the architectural design
- Hide structural members for a clean finish
- Allow ease in construction for rapid construction, de-construction, transportation and re-construction
- Use repetitive, standard members
- Incorporate thermal and acoustical insulation within the structural members
- Lower life cycle management costs

Fiber Reinforced Polymer (FRP) sandwich panels were selected as the primary structural material as they satisfied all of these goals. FRP sandwich panels have been widely used by aerospace, military and specialty industries. Examples include temporary load bearing, temporary bridge decking and slab in harsh environments.

The use of sandwich panels is not common for housing construction. A standard or code is not yet available for the structural design of FRP sandwich panels. A pre-standard by the American Society of Civil Engineers (Ellingwood *et al.* 2010) addresses these members but this pre-standard is only in the standard development process. The lack of accepted standards and the lack of engineering students' exposure to this material over the typical engineering curriculum limit the use of this material. For this project, team BEMANY students explored designing with this material through a literature review, testing and modeling. This paper only includes the design process of the Solatrium.

FRP sandwich panels were used in the Solatrium project as floor, wall and roof panels. The panels consisted of 4.5mm thick glass FRP laminate skins supported by and tied together with through thickness fiber insertions. The core material was 81mm thick polyisocyanurate foam.

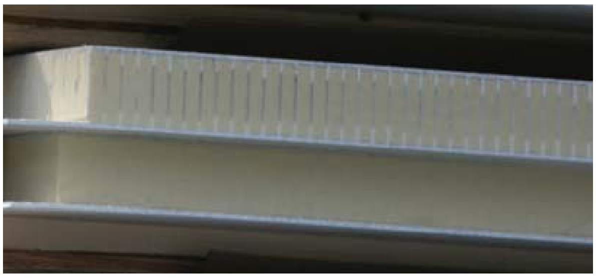

Figure 3. FRP Sandwich Panels

This material was found the most suitable for the project needs because FRP has a very high strength to weight ratio compared to traditional construction materials. Large openings were spanned by relatively shallow and significantly lighter members. The house created by FRP sandwich panels was much lighter compared to alternative materials, and therefore reduced the transportation cost from Worcester, Massachusetts to the competition in Datong, China. Light construction also reduces the earthquake loads which can be high for the competition location. Since the panels are lighter, no heavy construction equipment was required for the construction of the floor, wall or roof panels.

The panels were custom produced for this project by an automated technique called pultrusion. The same panels could be used as floor, wall and roof members. This allowed repetition in construction of the house. The repetitive nature of the construction significantly reduces construction time. Since the house was planned to be built in Worcester and then shipped to China, the modular nature of the standard shape panels proved very effective.

Architecturally, the panels provide a smooth surface without the need for additional finishing. The foam core provides thermal and acoustical insulation for the house. FRP as a material is known and preferred for its resistance to corrosion. This feature reduces the life cycle costs for the house, making the structure sustainable in the long term.

Where FRP sandwich panels were not sufficient alone, FRP pultruded shapes were used. FRP pultruded box beams, angles and I sections were used as foundation members, beams and columns. The box shaped columns were inserted into the FRP sandwich wall panels and therefore were mostly invisible. The only part of the project that required steel was the steel truss that was used to support the atrium roof.

Even though FRP has very low thermal conductivity compared to steel, one disadvantage of using FRP members for this project is the low thermal mass of the material. This challenge was overcome by using passive cooling techniques through the use of concrete tiles that incorporate phase change materials. The phase-changing concrete floor material is intended to offset the low thermal mass of FRP and regulate temperatures within the house.

Another challenge was the low stiffness of FRP panels which leads to large deflections for some larger spans. The deflections needed to be controlled by additional innovative design solutions. For example, the largest span for the FRP atrium roof panels was supported by a steel cable stay truss. The tension in the cables can be adjusted to control deflections. This will be described in more detail in the following sections.

Structural Design

Loads

In addition to live loads, the dead load of the structure and the solar panels, wind, snow and earthquake loads were the other major loading types considered in the design. While the dead and live loads on the structure remain the same for Worcester, Massachusetts and Datong, China, the environmental loads change significantly between the two locations. For the initial and permanent location of the house, Worcester, Massachusetts, snow loads governed the design. For the competition location of the Solatrium, wind and earthquake loads governed the structural design. Multiple locations for the house challenged the globally formed team BEMANY to explore and compare the design practices and requirements of building codes of the competition and codes in the United States as well as China.

The Atrium

The atrium is designed to contribute to the architecture, market appeal, and solar application contests directly and indirectly to the energy balance and comfort zone contests. The atrium opening is 6.75m by 6.75m centered in the house. The roof of the atrium is 5.13m by 5.13m and is supported by a steel truss angled at 45 degrees. This roof section is additionally supported by a cable stayed truss as shown in figure 4.

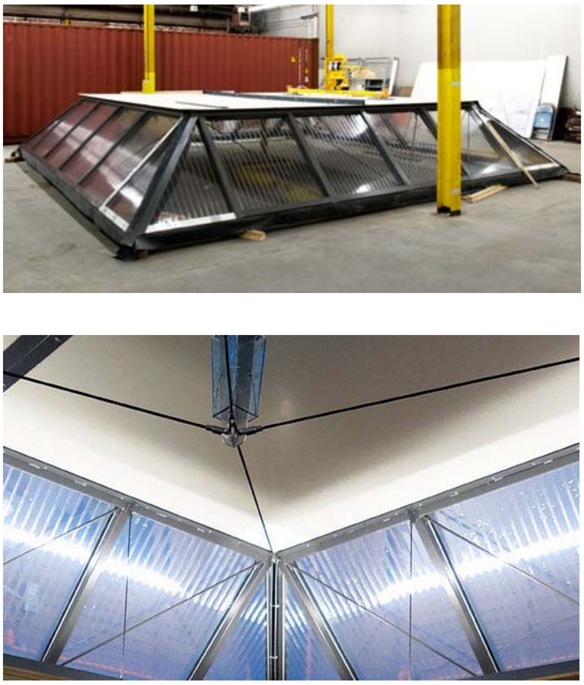

Figure 4. Atrium Truss and Panels

Due to the shipping size limitations, the atrium roof is composed of two FRP sandwich panels connected together along the mid-span line of the roof by angles bolted to each other. Due to the large span, the deflections controlled the design under the snow load in Massachusetts. The deflections of the sandwich panels alone were excessive. The cable stayed truss is designed to reduce the deflections of the roof. The roof sections were analyzed as planes using a finite element analysis. The deflections as obtained by the model are shown in figure 5.

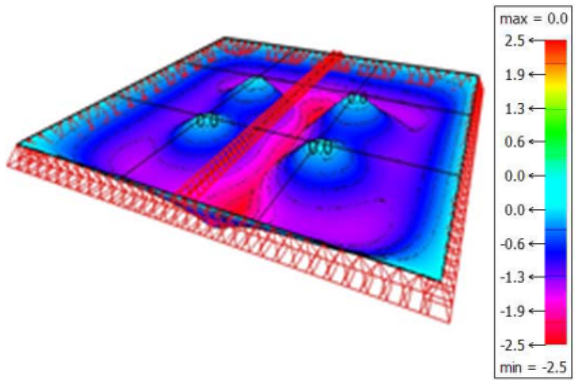

Figure 5. Finite Element Model Predicting Roof Deflections

The maximum deflection with the use of the cable truss system was 2.6mm meeting the serviceability criteria of maximum deflection smaller than one 360th of the span length.

The maximum deflection calculated was seen under snow load. When there is no snow, the tension in the cables can cause the roof panels to camber up. To prevent this, the tension in the cables will be adjusted to fit the site conditions.

The roof is supported by a steel truss system. The truss is angled which makes the connection details complicated.

The truss members are connected to each other by welding. The welding of the steel truss was done by students from a local technical high school-Worcester Technical High School. Involvement of the Worcester Technical High School added to the diversity of team BEMANY.

The truss and the roof panels are constructed as one assembly and will be assembled at grade level and will be lifted into place at once using a crane. This is the only part of the construction that requires heavy equipment.

Slabs

The same thickness FRP sandwich panels were used for the entire house including the slabs. This facilitates repeatability and modularization.

The roof slabs are supported by pultruded FRP beams. Since the atrium roof described earlier has a longer span, the sandwich panels used for the roof were adequate for other slabs with shorter spans as well.

The second largest span after the one for the atrium roof is 6m for the carport roof as shown in figure 1. This span will carry the same loads as the atrium roof (dead load, weight of the solar panels, snow load) and also experiences excessive deflections. To increase the stiffness of this span, an additional beam is placed on top of the slab to hide it from the users' view. This innovative solution makes the slab suspended from the beam.

Walls

Like the slabs, the walls of the house are made up of FRP sandwich panels. These panels have the strength to transfer gravity loads to the foundation. For the design, however, the walls are not relied on for carrying gravity loads. Instead the walls provide lateral stability during construction, and resistance to lateral loads, namely earthquake and wind loads. The locations of the structural walls are shown in blue color in figure 6. The walls transmit the forces to the foundation at column locations, through the columns embedded in them.

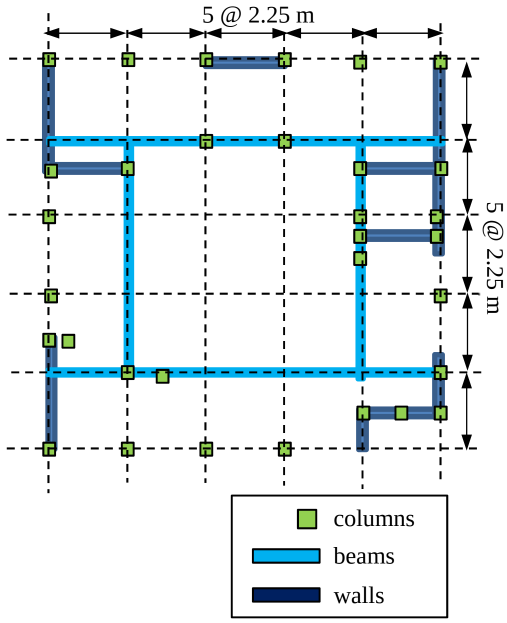

Figure 6. Beam, Column and Structural Wall Locations

A lateral load analysis of the house revealed the reactions on the column and walls. The Solar Decathlon Building code gives a basic seismic response factor of 0.15g in fortification 7 region. The earthquake load calculated using this factor was applied in each lateral direction of the house through a finite element model. The inter-story drift under earthquake loads applied in east-west direction of the house was 2.5mm. This corresponds to less than 1% of the story height. This low drift is expected since the house is made of a lighter material and has only one floor. Deflections under earthquake loads in the south-north direction of the house are given in figure 7.

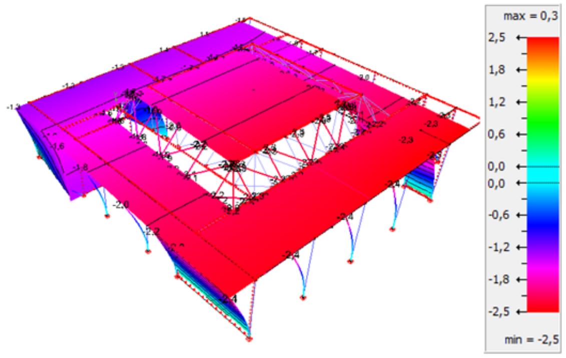

Figure 7. Deflections under Earthquake Loads

Figure 8 shows the maximum deflections expected on the house due to wind. The column and walls were checked to ensure they have the capacity to carry the reactions created by the wind load.

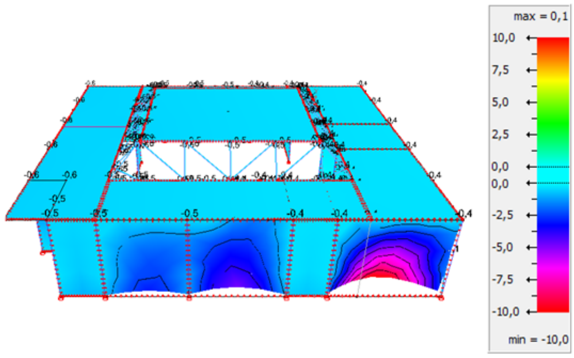

Figure 8. Deflections under Wind Load (mm)

Columns

Even though the FRP sandwich panel walls of the house have the structural capacity to transfer gravity loads to the foundation, this capacity was ignored as a conservative measure. This way, the uncertainties in the buckling strength of panels does not have an impact on the design. Instead, FRP columns were incorporated in the vertical panel edges to transfer gravity loads as well as to transfer lateral loads.

Column locations are shown in figure 6 in green. Columns adjacent to the walls were embedded into the sandwich panels by cutting through the foam to make room for the columns as shown in figure 9. Columns used in the solar house are pultruded FRP closed shapes. These sections were checked under combined axial load and flexure. The light weight nature of the pultruded shapes eliminated the need for any equipment for the erection of columns. Since the columns are embedded in walls, the walls also provide lateral bracing against buckling.

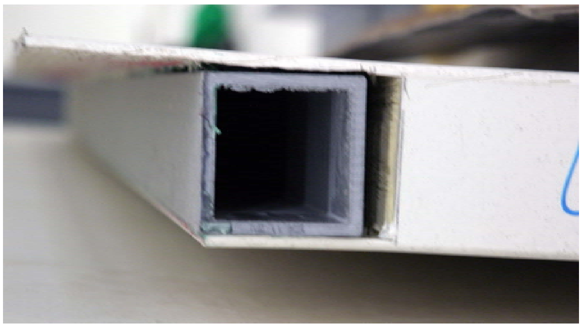

Figure 9. FRP Column Embedment in Wall Panel

Floors

The floors are supported by the foundation beams every 2.25m in each direction. They carry the concrete floor tiles in addition to the live loads, but no snow loads. Same size floor panels were oriented and placed as shown in figure 10.

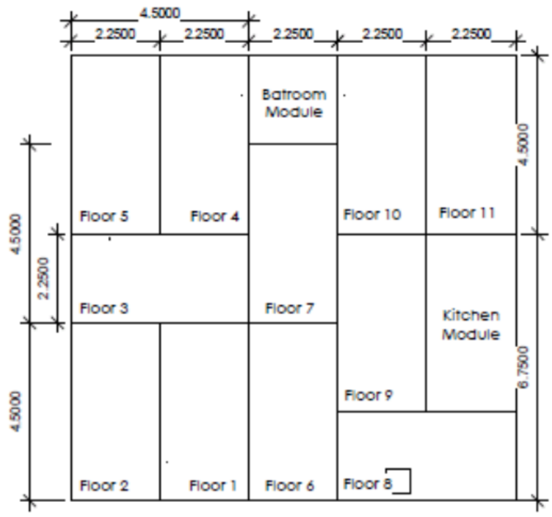

Figure 10. Arrangements of Floor Panels

Foundation

The foundation of the house is composed of pultruded FRP rectangular shapes. The finished foundation from the practice build is shown in figure 11.

Figure 11. FRP Pultruded Shapes for Foundation

According to the rules of the SD China competition, the foundation must be made to be adjustable for uneven terrain. To adhere to this rule, a foundation grid of FRP beams was designed with adjustable screw supports as shown in figure 12.

Figure 12. Screws to Align the FRP Foundation

Connections

Wall to column, and column to wall connections were provided using custom designed High Molecular Weight Polyethylene (HMWPE) connection cubes. A connected column (left) and a connection box with holes for the bolts (right) are shown in figure 13.

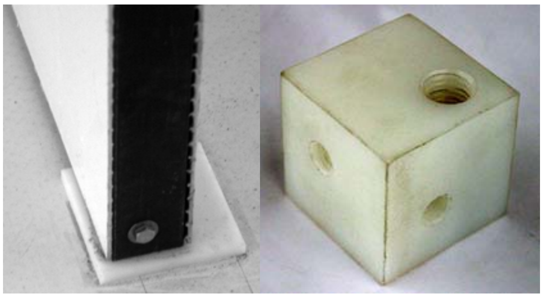

Figure 13. Column-Wall Connections

Structural Testing

Structural testing was performed on sandwich panels to ensure the capacities reported by the manufacturer were achieved, and to obtain the capacities that were not reported by the manufacturer. In addition, the sandwich panels were also tested for fire safety.

Final Completed Structure in Datong, China

Figure 14 shows the completed structure during the competition in Datong, China. The house was constructed, finished and functional within two weeks.

Figure 14. Finished Solatrium House in China

Design Process and Team Interactions

As stated before, the main design team is composed of over 30 students and faculty from three different institutions, with varying cultural backgrounds. Team members also have various technical focus areas in architecture, architectural engineering, structural engineering, fire protection engineering, civil engineering, communications, heating-ventilation-air conditioning (HVAC) engineering, welding. This great diversity equipped the team with a variety of ideas to tackle design problems.

Students in each group were supervised by faculty members in that specific area. Teams met internally as needed and the entire team met at least once a week to discuss progress. A communications team was formed to promote the project and communicate the process to the public and interested parties.

The global and technical diversity of the team also provided the students with the challenge to develop an understanding of the needs of different professions, preparing the students for a multi-disciplinary design world.

Students had to communicate with team members who were globally separated. This challenged the students to explore efficient communication and data sharing and compatible software alternatives. Software used by the engineers and architects were selected with compatibility in mind. Most project material was prepared digitally and shared online using free online data sharing systems. Use of building information modeling helped accelerate information sharing and coordination between team members. The design of the Solatrium simulated a design developed by a global design team. Students had to develop an understanding of different cultures and work environments.

Finally, the competition exposed the students to the latest technologies in sustainable housing design. WPI practices a project based curriculum where students are involved in at least two major projects during their undergraduate years. This project fits perfectly into the WPI curriculum which emphasized theory and practice together. Students had a chance to work on the Solar Decathlon project to fulfill their project credit requirements, or as an independent study. Students observed and became a part of the design process from the conceptualization to the building completion. Students learned to overcome obstacles in both technical areas and in areas that relate to communication. Any challenges were addressed by the related team members assuming ownership of the project.

Summary

This paper summarizes the structural design effort of the joint team, BEMANY to create a sustainable, affordable and efficient solar house. Team BEMANY's entry, Solatrium will compete at the Solar Decathlon China 2013 competition in Datong China. The structural components of the house were selected to best serve the needs of the architectural design and the competition requirements. The house is mainly built by using fiber reinforced composites. This unique aspect of the house constituted a challenge for the structural design. Students learned how to design, test, and build a house with a non-traditional construction material that is not covered in typical undergraduate curriculum or accepted building codes. Students also developed an understanding for the working process of multi-disciplinary, global design teams.

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Application of Phase Change Materials in Structures and Pavements

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Abstract: The need and desire for more energy efficient and environmentally friendly construction has motivated designers to find new construction techniques to achieve these goals. During the last decades, different new methods were proposed by designers to minimize the energy lost in buildings and to increase occupant comfort. Phase Change Materials (PCMs) have been accepted as a new additive to construction materials. Using PCMs in buildings decreases the energy lost in the structures and keeps the inside temperature closer to the desired temperature for a longer time. In addition, using PCMs in pavements increases their service life by decreasing the thermal deterioration due to freeze/thaw cycles experienced by the pavement.

Keywords: Phase Change Materials, Energy Saving, Service Life.

Introduction

The main new approach of construction is to design energy efficient structures (Chwieduk 2003; Papadopoulos *et al.* 2002). In buildings, a lot of energy is dissipated through the walls, roof, and floors; this energy dissipation can cause changes in interior temperature (Feng 2004). In order to increase the thermal inertia of a building's components, Phase Change Materials (PCMs) can be used in wall panels, roofs, tiles, ceiling insulations and other components of a building as internal energy storage. Due to their thermal properties, they can absorb heat energy during the day and release this energy to the environment during the night (Athienitis *et al.* 1997). In other words, PCMs act as passive interior energy storage units that cause the interior temperature profile to be smoother. This process not only decreases the energy usage in the structures, but also increases occupant comfort.

Another application of PCMs is in pavements and bridge decks. Roads and highways are one of the most important parts of the national infrastructure and different agencies annually spend a significant amount of money to keep pavements in good condition. In 2011 alone, the federal government and state departments of transportation spent over $100 billion on maintaining and improving core highways, roads, and bridges and roughly the same amount in the previous year (Federal HighwayAdministration 2012; The Department of the Treasury with the Council of Economic Advisers 2010). However, the quality of roads and highways are not satisfactory. In 2013, the American Society of Civil Engineers (ASCE) gave American roads a "grade" of D+, estimating that $3.6 trillion dollars of additional spending over the next decade will be needed to improve American infrastructure to a satisfactory condition (American Society of Civil Engineers 2009).

One of the causes of premature deterioration in pavements is extreme changes of temperature. A very low temperature causes tensile stresses in the binder and if these tensile stresses exceed the binder failure stress, thermal cracks develop in the asphalt mix layer of the pavement (Mallick *et al*. 2013; Qian*et al*. 2013). On the other hand, a very high temperature increases the likelihood of deformation related to shear stresses (Yun *et al.* 2013). Even if intense temperatures don't cause deterioration directly, cyclic changes in temperature cause failure in pavements after a long period of time (Kandhal and Rickards 2001).

A new option to decrease the deterioration of pavements due to extreme changes in the temperature could be the usage of PCMs as an additive to pavement materials. In the same way that PCMs smooth the temperature profile of a room or structure, PCMs will increase the service life of the pavements by smoothing the temperature profile that is experienced by the pavement. This paper will review the physicochemical properties of PCMs; provide several examples of field testing of the concept; and discuss the challenges to implementing designs with phase change materials.

Phase Change Materials

A PCM is a substance with a specific melting point and a high heat of fusion (Raoux and Wuttig 2009). When a PCM reaches the temperature at which it changes phase (e.g., melts), it absorbs large amounts of heat and remains at an almost constant temperature. The PCM continues to absorb heat without a significant rise in the temperature until all of the PCM is transformed to the liquid phase. When the ambient temperature around a liquid PCM falls under the melting point, the PCM begins to solidify. As it does, it releases the stored energy and again remains at an almost constant temperature. Therefore PCMs are capable of storing and releasing large amounts of energy and are classified as latent heat storage (LHS) units (Farid *et al.* 2004). The changes in the volume of PCMs during phase changes are extremely small and do not hinder the use of PCMs in construction materials. (Water would serve as an excellent PCM, with a very high heat of fusion at 334 kJ/kg, however, the melting temperature is not in the human comfort zone, and a volumetric expansion of some 12 % occurs during the transformation to ice (Hepler 1969)).

A large number of PCMs are available in any required temperature range from -33 °C to 800 °C (Zalba *et al.* 2003). Within the human comfort range between 20 °C and 30 °C, some PCMs are very effective. They store 5 to 14 times more heat per unit volume than conventional storage materials such as masonry or rock (Sharma *et al.* 2009). A list of some of the commercially available PCMs, by melting point and latent heat of fusion, is provided in table 1.

Table 1. Commercial PCMs Available on the Market (Zalba *et al.* 2003)

Material	Melting Point °C (°F)	Latent Heat kJ/kg (cal/g)
SN26	-26 (-14.8)	268 (64.0)
SN15	-11 (12.2)	311 (74.3)
SN06	-6 (21.2)	286 (68.3)
RT5	9 (48.2)	205 (48.9)
RT25	26 (78.8)	232 (55.4)
RT50	54 (129.2)	195 (46.6)
RT90	90 (194.0)	197 (47.1)

PCMs are divided into three main groups: Organic, Inorganic, and Eutectics. Organic PCMs are in general chemically stable compounds with a high latent heat of fusion. The thermal conductivity of these PCMs is low. This will increase the thermal resistance of the element that the PCM is used in. Therefore, higher thermal gradients and heat transfer rates are required to cause temperature changes (Baetens *et al.* 2010). Inorganic compounds in general have higher thermal conductivity and are cheaper. These PCMs have high volumetric latent heat storage capacity but the changes of volume in these PCMs are high (Baetens *et al*. 2010). Eutectic mixtures have a higher storage density than organic PCMs, have sharp melting points, and generally have the lowest melting points (Baetens *et al*. 2010).

During the last few decades, PCMs have been accepted as new materials and additives with various usages in industrial applications. Farid *et al.* (2004) introduced PCMs as a possible alternative to conventional satellite solar power generation systems. As a thermal storage unit, PCMs are also used in air conditioning systems in buildings (Nagano *et al.* 2006). The application of PCMs in smart textiles and clothes is also discussed by Mondal (2008).

PCMs can also be considered as an additive to construction and pavement materials. Using PCMs in buildings increases the thermal inertia of the structures and not only prevents rapid changes in the inside temperature, but also saves more energy by decreasing the energy needed to heat up and cool down the structure. In pavements, the number of freeze/thaw cycles of the pavement will decrease and also by using a PCM with a high melting point, rutting deterioration will be minimized. They can also be used in water storage systems, dams and marine structures with harsh changes in temperature. In the following, the application and practical considerations of PCMs in structures and pavements are presented.

PCMs in Structures

One of the important goals in construction technology is to design and build a structure that consumes less energy. Using less energy not only reduces the cost to the residents, but also decreases the emission of harmful gases like CO_2 into the atmosphere. Designers also look for a technique to keep the inside temperature in the comfort range and prevent rapid changes in room temperatures.

One of the primary ways to improve energy conservation in buildings and reduce the amount of energy input into the system is to use materials with low thermal conductivity and high specific heat capacity. The basic equation of 1D heat flow is presented in equation 1,

$$Q = -kA\frac{T_1 - T_2}{d} \tag{1}$$

where Q is the heat transfer rate (J), k is the thermal conductivity (W/m◦K), A is the area (m^2), T_1 and T_2 are the greater and lower temperatures, respectively (°C), and d is the distance between T_1 and T_2 (m). As can be inferred from the equation, by decreasing the thermal conductivity of construction components, the amount of dissipated energy in the structures can be decreased.

Because of their thermal properties, PCMs can decrease the thermal conductivity of the building components and also can be considered as passive interior energy storage units to save thermal energy in the buildings. Also, as the change in their volume is negligible, they don't cause any damage or cracks in concrete and other construction materials (Raoux and Wuttig 2009).

Based on the results of research by Khudhair *et al.* (2004), energy storage in the walls, ceiling, and floor of buildings can be enhanced by encapsulating suitable PCMs within these surfaces to capture and reserve solar energy. It also increases human comfort by decreasing the frequency of internal air temperature swings and maintaining the temperature closer to the desired temperature for a longer period of time.

A simulation by Athienitic *et al.* (1997) also shows that the utilization of PCM gypsum board may reduce the maximum room temperature by about 4 °C during the day and can significantly reduce the heating load at night. The schematic of an outdoor test room used in their research is shown in figure 1. Kissock *et al.* (1998) studied the thermal performance of wallboards imbibed in to the PCM. The results indicate that the peak temperature in the wallboards containing a PCM were up to 10 °C lower than in the control test cell during sunny days.

The results of a set of experiments by Hunger *et al.* (2009) also showed that using PCMs in concrete leads to lower thermal conductivity and increase in the heat capacity, which both significantly improve the thermal performance of concrete. Marble powder containing a microencapsulated PCM was used. Based on the micro structural analysis, a large proportion of the capsules were destroyed during the mixing process and the encapsulated paraffin wax was released into the surrounding matrix.

One of the most important issues about concrete is the hydration reaction between water and cement that creates the phases responsible for the strength of concrete. Anything that affects this reaction (such as the PCM leaking out of microcapsules) will decrease the compressive strength of the concrete. The compressive strength of samples containing 3 wt.% PCM was lower than the control samples which shows microencapsulated PCMs are not suitable for the requirements of a concrete application.

To add PCMs to concrete and prevent the harmful effects of the PCM on the hydration reaction, a new technique was proposed by Bentz and Turpin (2007). In this method, Light Weight Aggregates (LWAs) were used to incorporate the PCM. LWAs are porous aggregates that can absorb liquids by capillary action. Due to their porous nature and reasonably high absorption capacity, the LWA can be used as a carrier unit for PCMs. The research also showed that an LWA with an absorption capacity of about 20 % by mass could be used to incorporate about 350 kg/m^3 of PCM in a typical concrete. This amount of PCM could limit the repetitive temperature rise and decrease of a concrete section. Therefore, LWA presoaked in a PCM can be used in concrete and other construction elements. The LWA holds the PCM inside its porosity and prevents the reaction of the PCM with cement and water. Therefore the early age strength of concrete will not be affected by PCM. The final result is to have a new concrete with high strength and with higher thermal inertia.

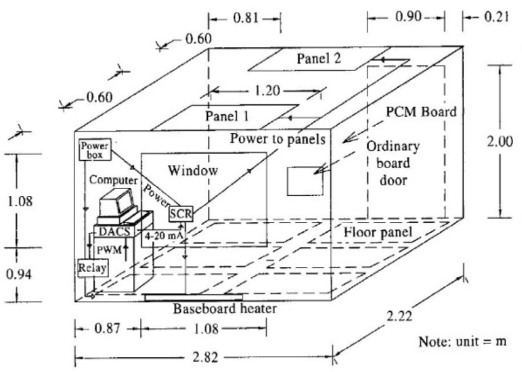

Figure 1. Schematic of Outdoor Test-Room (Athienitis et al. 1997)

Another possibility for applying PCMs to building construction is via PCM enhanced clay tiles. By using PCMs in the floor tiles, the annual heating costs of a building can be reduced by up to 24% (Hittle 2002).

It is currently possible for architects, owners, or construction managers to consider incorporating PCMs during the design phase of buildings. BASF, in particular, has developed a number of commercial products. One example is 'Smartboard', a gypsum wallboard that is embedded with BASF's Micronal PCM. This product is used in the same manner as conventional wallboard, with any additional cost to be recouped by energy savings during the occupancy phase.

The effects of Smartboard depend on location; however, a BASF study of six European cities indicated that the use of PCM-impregnated products significantly reduces heating and cooling energy demands, primary energy, and the CO_2 produced. The use of PCM incorporated wallboard or floor tiles may not be appropriate in locations with mild weather, however, the reduction in energy costs elsewhere over the life cycle of the building can add up to a substantial amount, though the initial investment may be somewhat increased.

Products such as Smart-board are meeting increasing acceptance in the industry, due primarily to widely publicized case studies such as the ones mentioned above. Further acceptance, however, must come from all stakeholders, primarily building owners/operators. Professionals concerned with the overall structure design may not be interested in such finishing touches; while those actually carrying out construction are under pressure to keep costs as low as possible in the short term (Berardi 2013).

Selection criteria of phase change materials for construction purposes can be divided into three main categories: thermodynamic, chemical, and economic properties. High latent heat of fusion and small volume changes during phase transformation are the preferred thermodynamic properties of a PCM. In addition, the melting point of the selected PCM should be in the range that has the best outcome. If the surface temperature of the structural component is supposed to be kept above the freezing point, PCMs with melting point between 0 to 4°C should be selected. But if the occupant comfort is desired, PCMs with melting point between 18 to 25°C could be more useful. The thermal conductivity of the PCM is also an important property. If the thermal conductivity is too high, more energy is dissipated and if it is too low, the released energy from the PCM will not be distributed through the media.

Chemical properties can be described as chemical stability, no reaction with construction materials, and no molecular degradation after a large number of freeze/thaw cycles, non-corrosiveness, non-toxicity, and non-flammability. If the PCM reacts with cement, the compressive strength of the concrete will decrease drastically. Therefore, for structural elements, PCMs with the least reaction with cement should be selected. But for nonstructural elements such as wallboard and tiles, PCMs with high latent heat which have a high level of reaction with cement can be used. Availability and low cost are two other important economic criteria to consider during the selection of a PCM.

PCMs in Pavements

The replacement of pavements is expensive and time consuming. One of the most important causes of deterioration in pavements is related to thermal behavior. Therefore, a lot of research has been done to increase the service life of pavements by improving the thermal properties of asphalt and concrete pavements.

A series of laboratory tests and computational modeling were carried on by Stoll *et al*. (1996) to evaluate the application of PCMs in improving the thermal properties of asphalt and concrete materials. The specific design concepts were: PCM melt-mix pellets blended directly with the concrete, PCM gel contained in a series of metal or polymer tubes, PCM melt-mix strips, or PCM dry powder. The results demonstrated the potential capacity of PCMs to reduce the thermal deterioration of pavements. In some cases, the amount of time that a bridge surface spends frozen was reduced by 90 %. This would have the additional positive effect of greatly increasing motorist safety, by reducing the amount of ice that would form on the bridge. However, in the case where metal tubes filled with PCM were used, the PCM was concentrated in a few parts of the pavement and did not provide protection to the entire structure. Because of the low thermal conductivity of concrete and asphalt, heat was not able to flow from the PCM and metal into the pavement. Moreover, no test was done to examine the effects of using PCM on the compressive strength or wear properties of the pavement.

Research was conducted in Japan to evaluate the use of PCMs in increasing pavement service life and to reduce the traffic accidents due to frozen water and snow (Miyamoto and Takeuchi 2002). Rectangular steel pipes (figure 2) filled with PCMs were used to increase the latent heat capacity of the pavement. The PCM had a phase change temperature of 3.1 °C, slightly above freezing. The solar energy saved during the day by the PCM was released at night and prevented the surface from freezing. Although the results demonstrate the capability of PCMs to improve thermal properties of the pavements, this particular technique was deemed too complicated and expensive for practical application.

Figure 2. Steel Pipes full of PCM (Miyamoto and Takeuchi 2002)

The effects of PCMs on thermal and mechanical properties of asphalt mixtures were studied by Chen *et al*. (2012). The results of laboratory tests show higher volumetric heat capacity and better low-temperature cracking resistance for the samples with PCM. However, as the PCM was added to the mixtures directly and because of the chemical reactions between the PCM and the hot mix asphalt, the indirect tensile strength and rutting resistance of the mixtures were decreased.

Figure 3. Locations in which incorporation of 50 kg/m3 of PCM increases bridge deck service life by less than 1 year (◊) or more than 1 year (•) (Sakulich and Bentz, 2012a). The gray zones show estimated areas of effectiveness for this technology.

To mitigate the chemical effects of PCMs in the hydration reaction of concrete, the application of impregnated LWA by PCMs to increase the service life of bridge decks was studied by Sakulich and Bentz (2012a; 2012b). The studies propose a practical and inexpensive way to incorporate PCMs in concrete pavement materials. As the PCM was encapsulated in the LWA, it didn't affect the hydration reaction between cement and water and the compressive strength of the concrete was not decreased drastically. In addition, the LWA particles are scattered in the whole volume of the bridge deck, which eliminates the problems associated with concentration of the PCM in specific points of the pavement. The existence of PCM in the pavement increased the service life of the pavement by decreasing the depth of freezing and the number of the freeze/thaw cycles experienced by the pavement.

To investigate the increase in the service life of the bridges decks in different locations of the United States, a computational simulation was conducted for eight different mixtures incorporating PCM (Sakulich and Bentz 2012a). This simulation was based on the CONCTEMP program developed at the National Institute of Standards and Technology (Bentz 2000). This program used weather information provided by the Typical Meteorological Year 2 (TMY2) data produced by the National Renewable Energy Laboratory to simulate the weather in 239 locations across the country. These files include such variables as cloud cover, wind speed, precipitation, etc. Heat transfer due to convection, conduction, incident solar radiation, and black body emissivity are considered by the program, which estimates temperature and time of wetness of bridge decks and pavements. This was combined with a service life model developed by Barde *et al*. (2009) for the Indiana Department of Transportation.

Basically freeze/thaw deterioration in pavements takes place in locations that have high level of humidity and low temperature. In these locations the cold weather causes the existent water inside the pavement turns to ice. The computational simulation also concluded that freeze/thaw is not a major concern in locations that are either too warm (the gulf coast and southwest) or too dry (the plains states). The incorporation of a conservative 50 kg/m3 PCM in concrete pavements was estimated to increase the service life of bridge decks by at least one year by reducing freeze/thaw damage in two general locations: the Pacific Northwest, and across the South (figure 3).

There is currently no way for those involved in the design or construction of bridges to incorporate PCMs in bridge decks. This technology is still very much in the development phase. The use of LWA in general is slowly gaining acceptance due to its association with the technique known as 'internal curing'. Additional research, the development of standards, and case studies will need to be carried out before the incorporation of PCMs in pavement materials meets widespread acceptance.

Conclusion

The main new approach of construction is to design structures the can save more energy and are environmentally friendly. Phase Change Materials are introduced as a new additive to construction materials to increase the thermal inertia of building components. PCMs can absorb a large amount of energy at almost constant temperature and release the reserved heat when the ambient temperature falls under the melting point. Therefore using PCMs in structures can save more heat energy and also increase the occupant comfort by decreasing the harsh changes in the inside temperature. In addition, using PCMs in pavements and bridge decks can increase the service life by decreasing the number of freeze/thaw cycles experienced by the pavement.

The PCM that is selected to be used should have high latent heat of fusion, proper thermal conductivity and be compatible with the construction materials. Availability and low cost are two other important criteria to select a PCM. Using metal pipes filled by PCM is complicated, expensive, inefficient, and generally impractical. Using LWAs as carrier agents for PCMs shows promise. The impregnated LWAs prevent the effects of PCM on hydration reactions. They are also scattered all over the unit and effectively can improve the thermal properties of construction and pavement components.

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Materials Science in the Design of Marine Infrastructure

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Abstract: Transportation infrastructure is critical to the health of any modern economy. In the United States, at least 70% of imports and exports pass through marine facilities such as ports. These ports, though critical to the national economy, are not immune from the growing infrastructure maintenance crisis. Materials science can be a key tool in designing marine infrastructure with enhanced durability. This requires an understanding of both physicochemical material properties and deterioration mechanisms. This paper discusses the benefits of using non-OPC alternative binders in marine infrastructure and the special considerations that must be addressed.

Keywords: Materials Science, Alternative Cement, Diffusion, Corrosion, Chlorides.

Introduction

Designing any structure requires an understanding of the physical and chemical properties of the materials to be used; how to custom-tailor those properties for a particular application (e.g. mitigating unwanted shrinkage); and an understanding of the environment in which the material is expected to perform. Modern design in the discipline of civil engineering has put a strong emphasis on examining and planning the impacts of development. By including the material properties in the design process, one can predict and account for these impacts and have better control by allowing an additional variable that can be matched with a specific need or problem (i.e. corrosion). This method of thinking can be applied to a multitude of common civil engineering design problems. This is especially true with the design of infrastructure, which, in nature, demands large quantities of physical resources. One such type of infrastructure that is normally overlooked is marine infrastructure.

In a modern society, trade and transportation are important to the health of an economy. Waterways have been used throughout history to move goods and products quickly. Today, U.S. waterborne freight (imports and exports) made up 42% of total trade at \$1.41 trillion in 2010. It was estimated that 566 million tons of goods were moved on U.S. inland waterways. 2.3 billion tons were move though U.S. marine ports encompassing more than 70% of traded commodities by weight. (ASCE 2012).

The U.S. is facing a growing infrastructure maintenance crisis, to which waterways are not immune. Many of the built systems in the U.S. are severely behind on maintenance and are in desperate need of repairs, upgrades, and rehabilitation. The principle issue in infrastructure maintenance is the significant cost. Over \$100bn is spent on maintenance yearly, however, the cost due to salt corrosion alone is estimated at over \$150bn (Davalos 2012).

The durability of infrastructure is directly relatable to economic and environmental sustainability. If the durability of a concrete structure was increased from a lifespan of 50 years to 500 years, the environmental impact and cost from the creation, transportation, and construction of the structure would be reduced by 10. This simple relationship can be explained by the fact that less material is being used which saves on the need for raw materials, energy, and ancillary effects such as the creation of construction-related congestion (Mora 2007). Designing structures for increased durability requires an understanding of not just the structure to be built, but the materials from which it is to be built and the deterioration mechanisms that affect it.

Figure 1. Attack by aggressive media such as chlorides can cause rapid deterioration of mechanical properties in infrastructure systems. Image reproduced from (Zolfagharifard 2011).

Many deterioration mechanisms plague marine environments, but the most critical is the corrosion of the embedded steel. Chloride ions diffuse through the binder of concrete and attack the steel reinforcement. This creates expansive products that cause internal stress, leading to cracking (Stewart *et al.* 2012). Cracking not only immediately reduces the mechanical properties of the system, but accelerates deterioration by providing aggressive media such as chloride ions easy access to the interior of the structure (figure 1).

The durability of a reinforced concrete structure is dependent on the susceptibility of the steel reinforcement to corrosion. A quality concrete is needed to minimize the penetration of chloride ions and other aggressive media. These agents permeate through the cementitious binder paste, moving especially quickly through pores in the material (Verbeck 1975). The composition of the concrete used will directly affect the durability of the concrete. Binders can be chosen for their transport properties, chemical properties, pore size distribution, pore solution composition, and other properties to reduce internal cracking and chloride diffusion (Bentz *et al.* 2008; Bentz *et al.* 2010).

Many kinds of materials and variants of common materials (e.g. Types 1-4 Ordinary Portland Cement) exist. It is incumbent on the designer to decide the most appropriate material. Here, recommendations regarding the design of marine structures are examined.

Materials Selection

OPC-based binders are by far the most important and widely produced infrastructure material worldwide. There are, however, a variety of alternative binders based on different chemistries. Calcium aluminate, calcium sulfoaluminate, and supersulfated cements each have their own unique chemistry and applications, but are generally relegated to niche markets (Sakulich 2011).

The most promising alternative cement is based on the alkali activation of slag. When slag, the molten waste product produced during ore refining, is water quenched, the molecular structure remains amorphous. After grinding into a powder, this material (usually called Granulated Ground Blast Furnace Slag, GGBFS) can be mixed with an alkaline solution. The result is a dense, solid form that resembles an OPC-based binder (Ŝkvára 2007). Due to the chemical makeup of amorphous slag, the primary strength-bearing phases in alkali activated slag (AAS) and OPC binders are generally the same: various calcium silicate hydrates (C-S-H). Depending on the initial reactants, however, the exact chemical ratios of the C-S-H can vary (Shi 1996). Although AAS and OPC binders have many similar material properties, such as comparable compressive strengths, shrinkage in AAS binders is significantly more pronounced.

AAS Shrinkage – Origins

Due to their similar chemistry, the origins of shrinkage are the same in AAS systems as they are in OPC-based binders. When water is added to OPC (or when an activating solution is added to GGBFS), hydration reactions occur. The products of these reactions generally occupy a smaller volume than the raw material – this shrinkage due to hydration reactions is referred to as 'chemical shrinkage' (figure 2a-b.). Before the binder has set, that is, before enough strength-bearing phases have been created to allow the binder to resist mechanical loading, chemical shrinkage has relatively little effect (Bentz 2007). Since the binder is still in a fluid state, the chemical shrinkage is not resisted. After setting, however, the binder is strong enough to resist deformation. Chemical shrinkage thus creates microscopic pores, generally evenly distributed, throughout the entire cementitious body. Chemical shrinkage leads to no detectable volumetric change in a cementitious body (Melo Neto 2008; Cincotto *et al.* 2008).

These microscopic pores are initially filled with pore solution – a combination of the original mix water (or activator solution) and various ions leached out of the cement or slag particles. As hydration reactions continue, these pores become larger at the same time that the solution is being consumed. The pores therefore become partially empty and the surface tension of the pore solution creates menisci within the pore (Sakulich and Bentz 2012). These forces are in turn the cause of 'autogenous shrinkage' – the menisci of the pore solution essentially attempt to pull the walls of the pore together (figure 2c.). This, in turn, creates a measurable shrinkage of the entire cementitious volume, and can lead to cracking in severe cases.

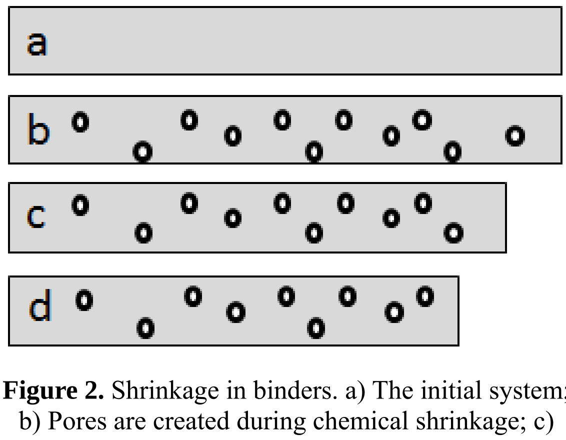

Figure 2. Shrinkage in binders. a) The initial system; b) Pores are created during chemical shrinkage; c) Autogenous shrinkage leads to a reduction in total volume; d) Further volume reductions are caused by drying shrinkage.

Finally, a third major type of shrinkage occurs in both AAS and OPC systems: drying shrinkage. Simply put, as water evaporates from the cementitious system, it leaves behind empty space (and helps to empty pores), which can cause shrinkage as well as cracking (figure 2d).

There exists a variety of other shrinkage mechanisms that may be at work in a binder, such as shrinkage due to mechanical deformation, temperature variations, creep, chemical attack, etc., however, these types of shrinkage are generally dependent on environment, whereas chemical, autogenous, and drying shrinkage occur in all binders, regardless of application or environment.

AAS Shrinkage – Measurement

Although chemical shrinkage produces no measurable volumetric shrinkage, it can be measured using laboratory glassware. A thin layer of binder is placed in a glass vial, which is filled with water. The vial is then plugged with a rubber stopper through which a capillary tube has been inserted. Since water can diffuse through very small distances very quickly, the pores of the binder will absorb liquid water from the vial almost as quickly as they empty. Observing the fall in water level via the capillary tube, the volume of pores created through chemical shrinkage can be deduced. This technique is outlined in ASTM standard method C1608 (ASTM International 2012).

Autogenous shrinkage is measured by a change in total volume. First, the binder is placed in a corrugated plastic "accordion tube" that does not resist deformation due to shrinkage. Once the material has set, the length is simply measured using a length comparator over a period of some weeks as outlined in ASTM standard method C1698 (ASTM International 2009a).

Drying shrinkage cannot itself be directly measured, since autogenous shrinkage and drying shrinkage occur concurrently. Instead, the total shrinkage of a binder is measured. A specimen is cast with metal stubs embedded in each end and held at a constant humidity and temperature. Each day, the length of the sample is measured; when autogenous shrinkage is subtracted from this total shrinkage, the result is the drying shrinkage. This measurement is outlined in ASTM standard method C596 (ASTM International 2009b).

AAS Shrinkage – Mitigation

In OPC binders, shrinkage mitigation is attempted most often through the use of shrinkage-reducing admixtures, fluids that are simply added to the binder during the mixing process. In essence, these admixtures reduce the surface tension of the pore solution. Surface tension (γ) is related to capillary stress (σ_{cap}) via the radius (*r*) of a given pore:

$$\sigma_{cap} = \frac{2\gamma}{r} \tag{1}$$

Capillary stress is itself directly proportional to the linear strain of the system (ε), that is to say, to the overall shrinkage of the system:

$$\varepsilon = \frac{S\sigma_{cap}}{3}\left(\frac{1}{K} - \frac{1}{K_s}\right) \tag{2}$$

where S is the saturation factor of the fluid-filled pores, and K and K_s are the bulk moduli of the porous material and the pore fluid, respectively. As such, reducing the surface tension of the pore fluid by a given amount usually reduces shrinkage by a similar amount (Bentz and Jensen 2004). Although many shrinkage reducing admixtures have been developed for OPC-based systems, they do not all work as well for AAS binders. The more aggressive pore solution (a result of the high-pH activating solution that must be used) generally causes structural breakdowns and a loss of effectiveness in the large organic molecules that are used in shrinkage reducing admixtures (Palacios and Puertas 2007).

Internal Curing

Instead of reducing the surface tension of the pore solution, an alternative is to simply ensure that the pore remains filled. If this is the case, no meniscus will form, and the forces that cause autogenous shrinkage will not come into existence. In order to keep pores full of fluid, some sort of internal water-filled reservoir must be used. As the pores empty, a pressure gradient is created that forces the water out of the reservoir and into the pores. A number of materials have been used as internal reservoirs, including lightweight aggregates and superabsorbent polymers, both of which can hold liquids simply due to capillary action. The materials are soaked in water and then incorporated into the cementitious system during mixing (Bentz and Weiss 2010).

In order to determine the amount of internal reservoir (in this particular case, lightweight aggregate) is needed to mitigate autogenous shrinkage, the Bentz-Snyder equation is used (Bentz, Lura *et al.* 2005):

$$M_{LWA} = \frac{C_f \cdot CS \cdot \alpha_{max}}{S \cdot \phi_{LWA}} \tag{3}$$

in which M_{LWA} is the mass of lightweight aggregate to be added per unit volume of concrete or mortar (kg/m^3); C_f is the cement factor of the concrete or mortar (kg/m^3); CS is the maximum chemical shrinkage of the binder, generally reached after a few days and measured as described above (g H_2O/g binder powder); α_{max} is the expected maximum degree of hydration of the binder, which can be determined through such techniques as image analysis, compressive strength testing, or calorimetry; S is the degree of saturation of the lightweight aggregate (usually a value from zero to one); and ϕ_{LWA} is the amount of water released by the lightweight aggregate (kg H_2O/kg dry lightweight aggregate). It should be noted that this equation assumes that the water contained within the lightweight aggregate will be released after only a slight decrease in the internal humidity of the system.

Generally speaking, the LWA that would be most preferable has the highest S and ϕ_{LWA} values. Further, a small particle size would be preferable, since the reservoirs would be more evenly distributed through the cementitious body. With a smaller distance between the reservoirs and the pores, less time would be required for the diffusion of water and the prevention of self-desiccation.

Whether a marine structure is to be constructed of OPC or AAS binders; and if shrinkage in the AAS binder is to be mitigated through the use of conventional shrinkage reducing admixtures (which may not work) or through the use of internal curing, are questions at the heart of the design of the structure.

"VERDiCT" Technology

It should be noted that the internal reservoirs used for internal curing can hold fluids other than water, which can have a positive impact on both shrinkage and corrosion. Corrosive media, such as chloride ions, diffuse relatively slowly through solid binders; they diffuse much more quickly, however, through pore fluid. The relationship between the diffusion of an ion and the viscosity of the fluid through which it is moving is given by the Stokes-Einstein relationship:

$$D_O = \frac{k_B T}{6\pi\eta_O r} \tag{4}$$

in which D_o is the rate of diffusion, k_B is Boltzman's constant, T is temperature, r is the radius of the diffusing particle, and η_o is the viscosity of the bulk fluid through which the particle is diffusing (Bentz, Snyder *et al*. 2008, Bentz, Snyder *et al.* 2010). Essentially, doubling the viscosity of the pore solution should double the length of time that it takes aggressive media to reach reinforcing steel. Filling internal reservoirs not with water, but with more viscous fluids, should both keep the pores full (reducing shrinkage) and change pore solution viscosity (reducing corrosion by slowing aggressive ions). This method has been given the name Viscosity Enhancers Reducing Diffusion in Concrete Technology (VERDiCT) by its developers at the Department of Commerce's National Institute of Standards and Technology.

Material Properties and Performance

A binder used in marine infrastructure applications, regardless of chemical composition or origin, will face significant deterioration due to the diffusion of aggressive media, particularly chlorides from saltwater. Chloride ions diffuse through the cementitious matrix and, upon reaching a sufficient concentration, begin attacking reinforcing steel. The products of this attack (i.e. rust) are expansive; more rust is created, the expansive forces become greater, and at some point cracking occurs. Cracking can lead to an immediate reduction of mechanical properties as well as spalling (the loss of concrete cover). Spalling and cracking also accelerate the cycle of corrosion by providing aggressive media such as chlorides with easy access to reinforcing steel (Li and Li 2010).

Corrosion in AAS Binders

The mechanisms of corrosion, much like the mechanisms of shrinkage, are generally the same in both OPC and AAS binders. The material properties of AAS and OPC binders are, however, significantly different. The higher amount of silica in the C-S-H gel produced in AAS binders leads to a more expansive strength-bearing phase, and thus a more refined pore structure, compared to that of OPC. The pores in an AAS binder are, on average, of a lower diameter, farther apart, and less numerous than in an OPC binder (Bakharev, Sanjayan et al. 2000). As diffusion of chloride ions occurs much more quickly through pores, this reduction in total pore volume and average pore size means that chlorides diffuse less quickly into AAS binders. That is, chlorides diffuse less quickly through un-cracked AAS binders; should shrinkage, mechanical issues, or thermal cycling lead to cracking in an AAS system, any such advantage over an OPC-based binder is lost.

Effects of Internal Curing on Corrosion

Internal curing, which can eliminate autogenous shrinkage in binders, has a number of effects on corrosion. Because shrinkage is reduced or eliminated, the threat of cracking (and therefore accelerated corrosion) is significantly reduced.

Further, the modulus of lightweight aggregate is often much closer to the modulus of cement paste than the modulus of silica aggregate is; therefore, there is a reduced elastic mismatch that can cause micro-cracking around aggregates. Cracking around the aggregates, much like cracking in the bulk material, rapidly accelerates corrosion by providing aggressive media with ready access to reinforcing steel (Bentz 2009).

In non-porous silica aggregates (such as sand) water cannot be absorbed. It is therefore not infrequent for the aggregates to be covered by a film of water, which prevents the formation of a good bond between the aggregate and the cement paste matrix. This leads to a less dense aggregate/matrix interface, and higher rates of corrosion. When internal curing is used, water can interact with the lightweight aggregate freely, and a significantly denser interface can be observed (Bentz 2009).

Finally, it may be possible that the empty porosity in lightweight aggregates can accommodate the expansive deterioration products created by processes such as the corrosion of reinforcing steel. In theory, this accommodation would reduce the internal pressures created by the expansion of the various deterioration products, reducing resulting cracking and extending service life. While this has not yet been conclusively investigated, anecdotal evidence exists that suggests this might be the case (Holm and Bremner 2000).

Conclusions and Recommendations

An understanding of material science, and the corresponding complete understanding of material properties, is indispensable in the design of infrastructure systems. Only through an understanding of the durability of the materials of which is a system is composed can accurate predictions of system service life be made.

In the particular example of marine infrastructure systems, several recommendations can be made. First, AAS binders are less at risk of deterioration due to the presence of aggressive media such as chloride ions than OPC binders. To counteract higher levels of shrinkage in AAS binders, internal curing can be used. This technology further reduces the diffusion of chlorides through the cement paste, improving service life. The use of lightweight aggregates can also be used to deploy so-called VERDiCT technology, further improving service life.

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Impact of Corrosion Inhibitors on Design

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Abstract: Corrosion of reinforcing steel in concrete can cause premature deterioration in a structure. Although several methods are commonly used to mitigate corrosion, this paper focuses on corrosion inhibitors. Three corrosion inhibitors (calcium nitrite, migrating corrosion inhibitors, and bioactive agents) are examined in terms of their effect on the design of structures.

Keywords: Corrosion, Corrosion Inhibitors, Calcium Nitrite, Migrating Corrosion Inhibitors, Bioactive Agents.

Introduction

In maintaining a well-built infrastructure, the incorporation of corrosion mitigation techniques in the design of concrete structures with reinforcing steel is of great importance. American infrastructure is considered to be in poor condition with an overall grade of a D+ and a need for $3.6 trillion for a full restoration (Engineers 2013). Nearly 343,000 bridges and 18,000 parking structures in the United States are constructed from concrete with reinforcing steel. However, many of these structures face structural deficiency due to the corrosion of the embedded steel with an estimated need of $9.3 billion to repair the bridges and parking garages (Emmons 2006; Koch *et al.* 2002). An estimated $100 billion is spent each year around the world on maintaining and repairing corrosion related damage (Li *et al.* 2011). These statistics reinforce the importance of designing structures with corrosion mitigating techniques.

Several approaches have been adopted to prevent corrosion. Fusion bonded epoxy coated rebar (FBECR) can be used where epoxy powder (a dielectric which prevents chloride ions from passing through) is fused onto heated steel bars; the bars must be carefully handled so that the epoxy layer does not become disturbed. When using FBCER in bridge design, the lap length must be increased since the pull-out strength of the rebar is decreased due to the coating (Broomfield 1997; Manning 1996). On the other hand, galvanized reinforcement (which corrodes sacrificially) can be used as a corrosion prevention method without the concern of delicacy as with FBCER (Broomfield 1997). Stainless steel rebar is also a possibility because of its resistance to corrosion, but it is extremely expensive and requires special standards and specifications during design since it differs from carbon steel (Baddoo 2008).

Another method that can be used other than alternative rebar is a waterproofing membrane. By creating a barrier, the rebar in the concrete is able to be protected from corrosion induced by chloride ions, water, and oxygen. Since these membranes are sensitive and need to be handled with care, it is crucial that the details at the time of the design of the structure are carefully planned to insure proper drainage (Manning *et al.* 1995; Broomfield 1997).

Cathodic protection can also be used as a corrosion mitigation technique. This can be installed during the construction of a new structure for protection against possible corrosion or applied to an existing structure to control corrosion rates. A direct current is used to polarize the steel and repulse chloride ions; the anodes are slowly consumed. Using cathodic protection, however, negatively affects the concrete’s adhesion to the rebar (Pedeferri 1996).

A popular technique that can also be used for corrosion prevention is the use of corrosion inhibitors. Corrosion inhibitors are commonly known to be easy to incorporate into a concrete mix without generally disrupting the design (Broomfield 1997). This paper investigates three types of corrosion inhibitors (calcium nitrite, migrating corrosion inhibitors, and bioactive agents) and their impact on the overall design of a structure.

Corrosion of Steel in Concrete

Concrete typically has an alkaline pore solution (pH > 13.5) due to the presence of calcium, sodium, and potassium oxides (Ahmad 2003). This protects the reinforcing steel by keeping it passivated by allowing the thin iron oxide layer that is on the surface of the steel to remain stable (Söylev and Richardson 2008). The iron oxide layer can become destroyed (depassivated) and allow the rebar to corrode through two methods: the carbonation of concrete and chloride attack (Böhni 2005).

Corrosion of the embedded steel in concrete is an electrochemical process where corroded steel is transferred into the pore water and gives up electrons at the anode. Since the two electrons are given up in the anodic reaction, the cathodic reaction consumes the electrons as well as water and oxygen (equations. 1 and 2). This reaction forms hydroxyl ions which protect the reinforcing steel – this process is commonly referred to as cathodic protection. One way that a reaction can continue and form rust is through ferrous hydroxide turning into ferric hydroxide which in turn becomes ferric oxide (rust) (equations 3-5) (Broomfield 1997; Raupach 1996).

Anode: $Fe \rightarrow 2Fe^{2+} + 2e^-$ (1)

Cathode: $\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2(OH^-)$ (2)

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \quad (3)$$

$$4Fe(OH)_2 + O_2 + 2\,H_2O \rightarrow 4Fe(OH)_3 \quad (4)$$

$$2Fe(OH)_3 \rightarrow Fe_2O_3H_2O + 2H_2O \quad (5)$$

The main issue with the formation of rust is volumetric expansion, which creates a buildup of pressure causing cracking and eventually spalling of the concrete cover. This can lead to structural deficiency and affect the cosmetics of the structure (Cabrera 1996; Slater 1983).

Carbonation of Concrete

Carbonation of concrete is a chemical process. As carbon dioxide from the atmosphere comes in contact with concrete, half of the carbon dioxide will interact with calcium hydroxide (equation 6) and the other half will react with calcium silicate hydrate (C-S-H) by decalcifying the C-S-H. Both reactions will produce calcium carbonate (Park 2008;Talukdar *et al.* 2012).

$$CO_2 + Ca(OH)_2 \xrightarrow{H_2O} CaCO_3 + H_2O \quad (6)$$

The depth of carbonation can be determined by using Fick's first law (Houst *et al.* 2002):

$$x = \sqrt{\frac{2Dc}{a}}\sqrt{t} \quad (7)$$

where x is the carbonation depth at time t; D is the diffusion coefficient of CO_2 in carbonated concrete; a is the concentration of the reactive compounds (the necessary amount of CO_2 to carbonate alkaline material); and c is the CO_2 concentration in the atmosphere. By calculating and obtaining the carbonation depth, a structure can be better designed for the possible carbonation it may face and provide for a better understanding of the service life of the structure (Khunthongkeaw *et al.* 2006).

Chloride Attack

The most rapid means of chloride attack in concrete is through exposure to substances such as seawater, deicing salts, and chloride-containing floors. When chloride ingresses into concrete, it is capable of ruining the passivating film of the rebar, lowering the pore solution pH by lowering the solubility of $Ca(OH)_2$, raising the moisture content because of the formation of salts such as NaCl in the concrete and increasing the electrical conductivity, leading to corrosion of the rebar. If elements of the concrete are contaminated with chlorides such as chloride-containing water used during mixing, corrosion can begin early on. The ingress of chloride through reinforcing concrete can be described through using Fick's second law (Böhni 2005):

$$c(x,t) = c_s\left[1 - erfc\left(\frac{x}{2\sqrt{D_{eff,C} \cdot t}}\right)\right] \quad (8)$$

where $c(x,t)$ is the chloride content at depth x and time t; $erfc$ is the error function; $D_{eff,C}$ is the effective chloride diffusion coefficient; c_s is the surface or near surface chloride content; and x is the depth and t is the time.

By using equation 8 to predict the chloride ingress, the design of the concrete cover can be optimized to adequately account for the potential chloride induction (Luping and Gulikers 2007).

Corrosion Inhibitors

Corrosion inhibitors are widely used to prevent corrosion due to chloride ingress. This is accomplished by raising the quantity of chloride ions needed to initiate corrosion and to reduce the rate of corrosion once it does begin (Gaidis 2004). There are numerous types of corrosion inhibitors. Monticelli *et al.* (2000) investigated over 30 types of corrosion inhibitors and concluded that several inhibitors are quite effective.

Calcium nitrite

Calcium nitrite is an anodic inhibitor that is capable of producing a protective oxide film on the reinforcing steel bar that is far better than the naturally occurring film from concrete. Ferrous ions from the concrete interact with the calcium nitrite to produce the oxide film (Saricimen *et al.* 2002):

$$2Fe^{2+} + 2OH^- + 2NO_2^- \rightarrow 2NO + Fe_2O_3 + H_2O \quad (9)$$

When calcium nitrite is included in a concrete mixture, the strength of concrete is not negatively affected, however, the setting time of the concrete becomes reduced and therefore a retarder is needed.

Ann *et al.* (2006) demonstrated that calcium nitrite significantly reduced the rate of corrosion of the reinforcing steel due to chlorides and increased the chloride threshold level (the content of chloride to initiate corrosion of the reinforcing steel) to a range of 0.22 % - 1.95 % by weight of cement. However, the control specimens (no calcium nitrite) produced a chloride threshold level range of 0.18% - 0.33%. The Federal Highway Administration (FHWA) conducted a study on calcium nitrite where chlorides were directly added to the mix water of concrete batches with high w/c ratios (>0.5) and yet concluded that the calcium nitrite greatly reduced the corrosion rate (Saricimen *et al.* 2002).

Berke *et al.* (2004) created a model that demonstrates that design engineers can adjust the amount of calcium nitrite and the quality of the concrete and the concrete cover to obtain a desired service life of the structure in excess of 50 to 100 years. The model was able to show that a 100-year service life would require a high amount of calcium nitrite along with a low permeability of concrete (Berke *et al.* 2004). The low permeability will act as a protection layer for the rebar by making it more difficult for chloride ions to pass through.

Migrating Corrosion Inhibitors (MCI)

Migrating corrosion inhibitors are normally applied to the surface of concrete with reinforcing steel structures through methods of spraying, painting or rolling of the liquid solution. They are meant to penetrate through the surface and migrate throughout the concrete and reach the reinforcing steel (Bjegovic 1999; Tritthart 2003). Most MCIs are monoflurophosphate-based (MFP) or amino alcohol-based (AMA) inhibitors (Söylev *et al.* 2007).

MCIs can be transported through concrete in three ways: capillary suction, diffusion, or through a gaseous phase. Tritthart (2003) conducted an experimental design in order to better understand the transportation process of amino alcohol and phosphorous based MCIs. It was determined that the phosphorous compound is unable to penetrate from the surface of a structure due to the creation of insoluble calcium salts as the phosphorous diffuses through the cementitious binder. However, the amino alcohol dissolves into the pore solution and therefore is able to migrate throughout. Although transport of the amino alcohol is possible through the gaseous phase, it is not as efficient as diffusion. Capillary suction was determined to have little to no effect. Once the amino alcohol comes in contact with the rebar, a hydrophobic monomolecular layer is created by means of physical or chemical adsorption where the reinforcing steel is protected because the molecule separates the chloride ions, water, and oxygen (Zheng *et al.* 2012).

Zheng *et al.* (2012) conducted research on the durability of a concrete matrix with regards to the surface-applied AMA inhibitors. Results showed that the AMA concentration that reaches the rebar is low and not enough to protect the steel reinforcement. However, the AMA acts as a pore-blocker by suppressing the capillary absorption in the concrete which makes it difficult for the chloride ions to migrate within the concrete. This is a secondary effect but still protects the reinforcing steel from corrosion. Therefore the effectiveness of the corrosion inhibitor actually relied on the mix design of the concrete. Three water/cement ratios (w/c = 0.4, 0.5, and 0.6) were compared. It was found that as the w/c ratio increased, the effectiveness of the surface-applied AMA decreased due to the increased migratory routes for chloride ions since the concrete is less dense (Zheng *et al.* 2012).

Bioactive Agents

There has been much research invested in using natural products to prevent corrosion (Raja *et al.* 2008). Bioactive agents have been shown to prevent corrosion of stainless steel and aluminum. However, when these bioactive agents are simply mixed in with concrete, aspects of the concrete such as its compressive strength and set time are negatively affected (Jafferji *et al.* 2013). Bioactive agents can cover a cement particle's surface and therefore prevent the cement particle from reacting with water; hydration is affected and less C-S-H is produced, which negatively affects the compressive strength (Taylor 1997).

One study incorporated the use of a bioactive agent called cinnamaldehyde (CA - the active compound that gives cinnamon its aroma and flavor) by encapsulating it in lightweight aggregate (LWA). The goal was to include CA without interfering with the early age properties of the concrete (Jafferji *et al.* 2013).

LWA is porous where it is able to use its capillary action to absorb liquid and lock it away within itself. The liquid can then be released once the cement has undergone hydration reactions (Bentz and Weiss 2011). By using lightweight aggregate to store the CA and release it only after the cement has undergone its hydration reactions, the mechanical properties such as the strength of the concrete will not be affected.

However, the study was unable to achieve its goal of including the CA without its negative effects. The compressive strength of the specimen with the inclusion of CA was greatly reduced compared to the control (which did not include LWA or CA) and the control that included encapsulated water in the LWA.

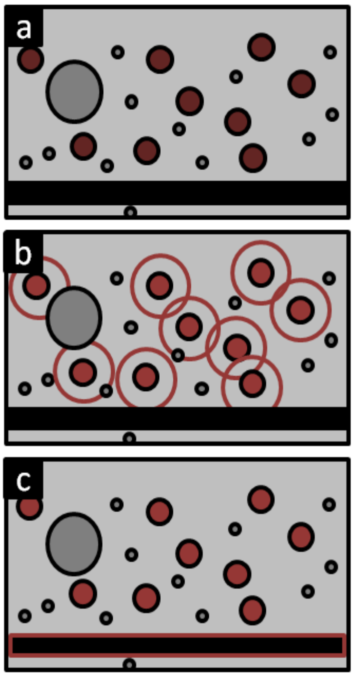

Figure 1. Schematic representation of the composite system, CA encapsulated in LWA a) the fresh mix contains cement (light gray), normal aggregate (dark gray spheres), LWA filled with bioactive agent (red), and a piece of rebar (black bar). Because the bioactive agent is 'locked away' it cannot interfere in the development of early age properties. b) After set, water is consumed in hydration reactions, leading to a pressure gradient that forces some bioactive agent to migrate out of the LWA. c) Over time, bioactive agent builds up on the surface of rebar and begins to play a role in corrosion mitigation.

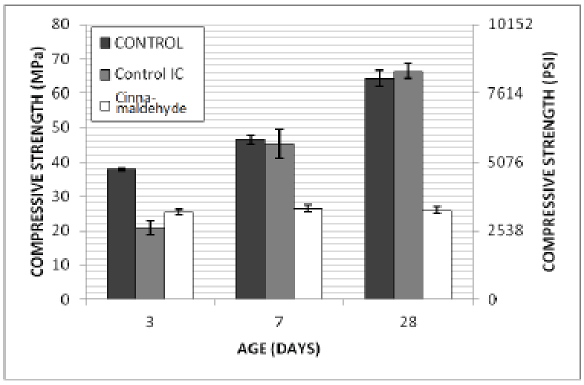

Figure 2. Compressive strengths of the control specimen (with no LWA or CA), internal curing (IC) control specimen (water encapsulated in LWA), and cinnamaldehyde specimen (CA encapsulated LWA). The compressive strength of the specimen with CA is greatly reduced compared to the control and IC control (Jafferji *et al.* 2013).

This may indicate that the LWA did not absorb all the CA, or that the CA is being released during the mixing, or that there is some CA on the surface of the aggregate (figures 1 and 2). Research continues with the aim of optimizing a mix design to include CA as well as other unconventional corrosion inhibitors with the use of lightweight aggregate (Jafferji *et al.* 2013).

Discussion

Corrosion inhibitors do not have a major effect on the actual design of a structure but rather can be noted as an added item to be accounted for in the design phase. The costs of using corrosion mitigation methods are far lower than the cost of repairing corrosion-damaged structures. These prevention techniques may add an extra step in the design phase but they may also help maintain the structure in the long run.

When calcium nitrite is to be incorporated in a mix, a retarder is required to account for its result in accelerating the setting time of concrete. Also, it is necessary to reduce the mix water to adjust for the water present in the inhibitor. Generally a calcium nitrite inhibitor will contain 30% calcium nitrite and 70% water. The guidelines specify to subtract seven pounds or 0.85 gal. of mix water per gallon of inhibitor. Calcium nitrite can come packaged in 1041 l (275 gal.) totes, 208 l (55 gallon) drums, and in bulk quantities. Based on a commercially available calcium nitrite corrosion inhibiting admixture, this inhibitor can be directly added to the batch water of the concrete. The prescribed amount to be used ranges from 10-30 L/m^3 (2-6 gal/yd^3) which relies on the chloride protection needed (specific to each project) (Euclid Chemical 2013).

Since MCIs are surface applied, the design is not affected. However, preferable design can be used to achieve best results (i.e. adjusting the water/cement ratio). MCIs come in 18 l (5 gal.) pails and 208 l (55 gal.) drums. When applying MCIs, a two coat minimum is recommended. The limitation to applying MCIs depends on the weather; if it is raining or snowing MCIs must not be applied to avoid surface interference (Sika Corporation 2013a; 2013b).

A case study on the 6th Street parking garage in Louisville, KY is a practical example of the versatility of a penetrating corrosion inhibitor. Built in 1987 this nine-level garage was constructed with cast-in-place, post-tensioned concrete. In 1990, there was an addition of a south bay. This garage faced an issue with spalling and it was determined that a high level of chloride content at the reinforcing steel was the main reason. A solution was needed to both repair the damage and prevent this from occurring in the future. Along with other repair and protection methods that were used as part of a solution to this issue, a penetrating corrosion inhibitor was chosen as part of the prevention method. Monitoring probes were used to check the corrosion rates of the garage prior to the restoration and after. It was concluded that corrosion rates were lowered and continue to be low (Sika Corporation 2013c).

Currently there is no commercially available lightweight aggregate/bioactive agent composite for corrosion mitigation. To integrate the composite aggregate in the mix design requires an aggregate screening since only a portion of the total aggregate will contain the composite aggregate. Therefore, some normal aggregate particles must be replaced with the composite aggregate. When using the composite aggregate, the aggregate particle size distribution of normal aggregate (i.e. sand) should not be disturbed. This is a critical aspect since it will affect the mix design with regards to the total aggregate to concrete ratio.

Conclusions and Recommendations

Corrosion of reinforcing steel in concrete structures can affect the structural components of the built environment. Incorporating corrosion inhibitors in a design can greatly help deter corrosion and prolong the service life of a building system. Aspects such as the mix design are shown to play a role in the effectiveness of the corrosion inhibitors. When mixing concrete with the inclusion of calcium nitrite, a retarder may be needed to offset the early setting time that is produced. For migrating corrosion inhibitors, the mix design with regards to the water/cement ratio is essential to the effectiveness of the corrosion inhibitor. Although, research is still being conducted on integrating bioactive agents with the use of lightweight aggregate to inhibit corrosion, an optimization of the mix design is crucial as to not interfere with the mechanical properties of concrete.

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Utilization of Shale Concrete for the Low Cost Housing Industry

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Abstract: This study focuses on the utilization of shale as an alternative material in concrete technology as a substitute for sand. Shale is an abundant kind of sedimentary rock that has both silt and clay present or is predominantly clay. Shale abundance is considered a disadvantage for it has no agricultural value, can choke streams and other waterways, may cause flooding, and has the potential to make an earth surface slip in mass wasting activities accredited to the shale fissile property. Standard concrete is composed of sand, gravel and cement. The alteration of the concrete components' physical and mechanical properties changes the functional performance. In this study, shale aggregates were taken from four different locations. The results are discussed from an axiomatic design approach. The compressive strength of hardened concrete is an index of its other properties as a basis for controlling quality and evaluating the effects of variable factors such as materials, proportion, manufacturing equipment and methods. In the design mix, it was found that Shale Concretes have a compressive strength ranging from 13 to 18 MPa, an average flexural strength of 2.64 MPa and a punching shear strength of about 2.64 MPa. Other concrete components in home construction include masonry. In this study it was found that the compressive strength of Shale Concrete Hollow Block ranges from 7.2 to 9.80 MPa. Furthermore, mortar using shale was also examined. It was found that shale aggregate can be utilized for plastering purposes. The strength of shale mortar paste ranges from 6 to 11 MPa. The design and construction methodology of a shale concrete house is also considered. It is shown that the cost of construction is reduced to 10% without sacrificing the structural requirements of a low cost house or small residence.

Keywords: Low Cost Housing, Shale Concrete, Shale Aggregate, Shale Concrete Hollow Blocks, Shale Plaster, Shale Mortar.

Introduction

Concrete is widely used as a building material in construction and infrastructure. Concrete consists of a hard inert material known as aggregate (fine for sand and coarse for gravel) bonded together with cement and water. The high demand for concrete in the coming years will be doubled or maybe even more because currently there are still many Filipinos without homes. Housing ownership in the Philippines is as low as 30% compared to neighboring countries like Singapore, Hong Kong and Taiwan which ranges from 70% and up. The very high demand of concrete caused significant depletion of the materials used in making concrete such as aggregates. Aggregates are fast becoming a non-renewable resource for the extraction rate is now higher than the deposition rate. Rapid population growth causes the increasing trend of natural resources consumption, which put pressure on the limited supply.

The availability of sand in Western Samar or in Samar is scarce because rivers in the province have inadequate sand resources. If the sand is available, it usually does not meet the required ASTM standards which the Philippines also use as a standard. The sand used usually comes from Dulag Leyte, Burauen Leyte and Tolosa Leyte where the aggregates are quarried. This is a 4 hour drive from Samar. The cost of delivery from these municipalities in Leyte to Samar Island adds to the high cost of the aggregate when it reaches the consumers. The transportation of aggregates also adds to CO_2 emissions and thereby contributes to climate change. It is believed that the resource may come to depletion. This will negatively affect local economic conditions and may even affect conditions at the global scale as well. It is for this reason that the cost of sand and gravel has quadrupled to date. Consequently, the housing industry costs rise and will eventually make housing unaffordable to low income families.

The government mandates its people through the issued PD 1594, sec.1, par. c, to help enhance the growth of the local construction industry by using indigenous materials in order to minimize the dwindling of our natural resources. In the Philippines, specifically in Samar, Llego (2000) found that crushed shale rock is a lightweight aggregate and can possibly substitute sand in making concrete.

Shale, is an abundant kind of sedimentary rock that has both silt and clay present or is predominantly clay. West (1995) estimated that the earth contains about 46% shale, followed by 32% sandstone, and 22% limestone. The study (Gilluly 1968) of geologists: Clarke's – Horn and Adams - Kuinen's show that vast volume of sedimentary rock supply covers more than two thirds of the land. The relative proportion of shale computed by different geologists as reported in measured strategic sections in percentage outcrop and percentage expected under differing assumptions of various authors are from 42 to 58 and 70 to 83 percent respectively. Keller (1992) noted that the abundance of shale resources may cause considerable environmental problems and its existence is a red flag to the applied earth.

The utilization of shale in its natural state as a 100% substitute for sand in concrete is referred to in this study as shale aggregate (SA). Before this can be done to reduce the environmental impact of construction, tests to determine the strength of shale aggregate and the product of using it as component material in concrete are needed. Also, cost reduction for both the materials and the labor components in building construction seems to be a complex problem that needs to be addressed. The process of the construction using this new material requires an evaluation. It is with these premises, this study was conducted to find the functional requirements (FRs) and design parameters (DPs) of shale as a fine aggregate in concrete technology and its criticism during construction.

Objectives

The main objective of the study is to find the utilization of the shale resource as a component of concrete for use in low cost houses or small buildings. According to Suh (2001), Axiomatic Design (AD) is a prescriptive engineering design method that defines design as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through a mapping between Functional Requirements (FRs) and Design Parameters (DP). AD is also a design theory that constitutes knowledge of basic and fundamental design elements. In this context, a scientific theory is defined as a theory comprised of fundamental knowledge areas in the form of perceptions and understandings of various entities and the relationship among these fundamental areas such as utilization of the shale aggregate to create a shale concrete (with shale as a fine aggregate in its natural state) and finding the stability, durability mechanism of shale concrete as structural concrete, masonry and plaster, and its cost in a 30 sq. m. small residential building. Specifically the study will determine the following:

1. Reducing the environmental impact of the utilization;
2. The Functional Requirements (FRs)
3. The Design Parameters (DPs)
   - Shale Concrete (SC) design mix;
   - Design mix for Shale Concrete Hollow Block (SCHB);
   - Design mix for Shale Plaster (SP);
   - Compressive strength,
   - Flexural strength, and
   - Punching shear strength of SC;
   - Compressive strength of SCHB
   - Adhesion of SP;
4. Design and cost of construction;
5. Construction issues

Methodology

This study uses laboratory experimentation to determine the design mixture of shale concrete (SC), shale concrete hollow blocks (SCHB) and shale plaster (SP). Field and literature surveys were made to determine its environmental impact and the design considerations of the design mix result in comparison to the standard. The construction process was also presented in response to the behavior of the new concrete product. The axiom of utilization is based on figure 1:

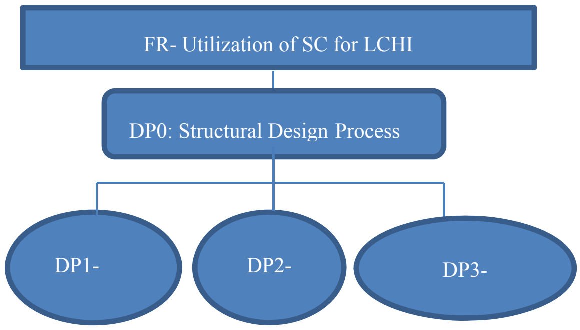

Figure 1. Axiomatic Design of Utilization

The structural design process is divided into three phases, i.e. planning, design and construction.

Phase I. *Planning***:** This phase involves the consideration of the various requirements and factors affecting the general layout and dimensions of the structure and results in the choice of one or perhaps several alternative types of structure. In this case, a small residential building offers the best general solution. The primary consideration is the function of the structure and this paper presents the strength of concrete. As a secondary consideration, the environment was also taken into account as discussed in the reduction of environmental impact of utilization.

Phase II. *Design***:** This phase involves a detailed consideration of the alternative solutions defined in the planning phase and results in the determination of the most suitable proportions, dimensions and details of the structural elements and connections for constructing each alternative structural arrangement being considered and presented here in matrix form.

Phase III. *Construction***:** This phase involves the mobilization of personnel; the procurement of materials and equipment, including their transportation to the site, and actual on-site erection. During this phase, some redesign may be required if unforeseen difficulties occur, such as the environmental condition of the structure where it will be built.

Result and Discussion

This study aims to determine the utilization of shale in its natural state used as a sand substitute for a fine aggregate in concrete for low cost houses. This study is an answer to the cry of low income earners to find alternative ways to build houses using available resource that have an adverse impact on the environment. This is an addition innovative approach to make housing available and affordable which is fast becoming popular in the provinces after becoming a success in big metropolitan areas like Metro Manila and Cebu in the Philippines.

Four shale samples were taken from four different locations in the Philippine Island, particularly in Samar namely: Barangay Laygayon in the Municipality of Pinabacdao, SSU Compound in the City of Catbalogan, Barangay Botoc in the Municpality of Jiabong and Downtown of the Municipality of Motiong Samar as shown in figure 2.

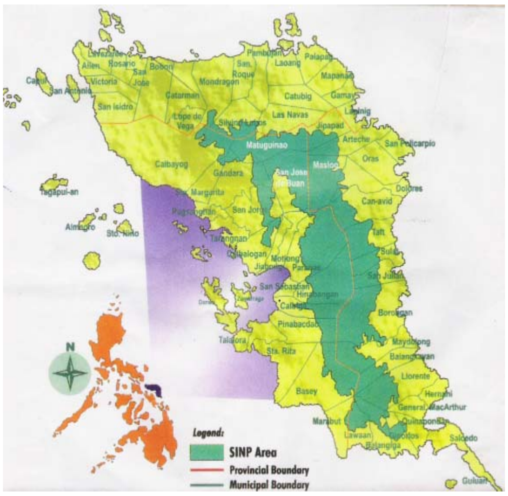

Figure 2. Study Area

Reducing Environmental Impact of Utilization

Components of concrete have a big impact on transportation energy use, water for washing, and dust generation. Using the shale resource in its natural state reduces the production of CO_2 because it is not kiln dried. Dust emissions during the crushing can be controlled through water sprays, enclosures and covered chutes.

In terms of the demand for concrete as the population increases, using conventional aggregate interlinked factors: P (population), I (an index of factors that can cause environmental damage as defined in the equation below where damage is a function of three industries) and urban growth W (an indicator of the degree to which culture promotes wasteful consumption of natural resources) (http:ecosmartconcrete.com/docs/trmehta01.pdf).

$$D = f(P \times I \times W) \tag{1}$$

Utilization of shale as concrete for low cost houses can minimize the hazards that the shale resources contributes to locally as shown in figure 3 and figure 4, by using it productively as concrete, the landslides and slips will be minimized.

Figure 3. Road Slips

Figure 3 above shows the common problem that occurs at locations where shale is prevalent despite re-surfacing and concreting. Figure 4 shows the continuous slides of shale on a newly constructed road in Barangay Laygayon of Pinabacdao municipality.

Figure 4. Land Slide

The extraction of the resource can be done by open pit mining and quarry. Excavating shale depends on the geologic characteristics, the extent and thickness of the deposit. According to West (1995) shale is categorized into two types, namely: compaction shale and cementation shale. Compaction shale is held together primarily by molecular attraction of the fine clay particles and is a very weak rock because: a) it has a high potential to slide even on gentle slopes depending upon the bonding between the depositional layers or bedding planes, b) it has a high potential to slake, that is water contact causes the surface to break away and curl up, c) it has a high potential for water absorption and it may swell depending on its mineralogy, d) because of its elasticity, these rocks are abundant throughout the globe and have value as a mixing substance in the manufacture of cement, e) these rocks have an unconfined compressive strength as low as 1.8 kg/sq.cm. On the other hand, the cemented shale can be very stable depending upon the degree and type of cementing material. It is a strong rock suitable for all engineering purposes. Shale has a compressive strength of 1,390 – 13,900 psi (qu); with a shear strength of 417 – 4,170 (So). Its modulus of elasticity is 1.4 to 4.9 x 10^6 psi (E) and its angle of shearing resistance is 15 – 30 (Φ). However, clay shale has a compressive strength of 180 – 1,040 psi (qu) and shear strength of 40 – 160 psi (So). Commonly it is excavated with conventional earth-moving equipment such as bulldozers, front-end loaders, and tractor scrapers. Shale resources do not require blasting, giving a reduction to the impact on or damage to the environment. However, depositions or stockpiling should be well managed. Stock piles should be covered from exposure to rain as the resource weathers easily due to its fissile property as shown in figure 5.

Figure 5. Gradual shale erosion due to overburden

Processing shale requires crushing to attain a fine aggregate. After crushing, the aggregate is sorted to size. No washing is done as shale components are silt and clay. At this stage, the aggregate is commonly moved by conveyors to bins or is stockpiled. In stockpiles, it should be covered so as to prevent the material from wetting as it will cause siltation and clog waterways. Finally, the aggregate is loaded on trucks for shipment to the site of use for concrete production. In as much that the material is locally sourced, CO_2 emissions will be less. Energy use is less intensive too. The environmental impact of the shale concrete industry can be reduced through resource productivity by conserving material and energy for concrete making and by improving the durability of concrete products, thus an FR and DP are discussed.

Functional Requirements (FRs)

Concrete as a man-made stone is ideal for residential building because it is a non-combustible material; fire-safe; able to stand high temperatures; resistant to wind, water, rodents, and insects; and is popular as it can be shaped accordingly. Concrete in this study is from a mixture of cement, shale (sand), and gravel called SC and is used primarily for structural purposes like columns, beams and foundations to create a better affordable shelter. Concrete is economical when the ingredients are readily available.

Low cost type or small type houses for which these concrete products are designed are one storey 30 sq.m. (5 m x 6 m). The dimension selection is based on the requirements for structural walls on 3 sides that according to the standard should not exceed 36 sq.m., and the height is 3 m. based on criteria for small building as shown in figure 6 which is widely accepted in the Philippines for affordability. Concrete masonry in hollow modular concrete block form as a building material is used for exterior and interior load bearing walls made from cement, shale and water, known here as Shale Concrete Hollow Block (SCHB). To produce a uniform finish of the SCHB and SC for aesthetics purposes of a house a mortar is taken to account called here are Shale Plaster (SP).

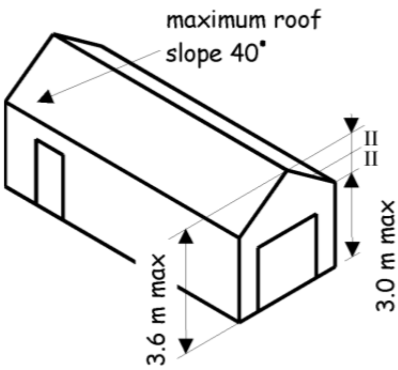

Figure 6. House Height

The dimensions of the house are minimized so the design conditions are not complex. Concrete does have some limitations despite the numerous advantages mentioned earlier because concrete has a relatively low tensile strength, low ductility, low strength-to-weight ratio, and is susceptible to cracking (http://matse1.illonois.edu/concrete/prin.html). A new material introduces new technology and a different form inevitably evolves as discussed below.

Design Parameters (DPs)

The design parameters considered in making concrete are durability, workability, and the strength of concrete. For aggregate production, techniques such as quarrying, stocking and aggregation methods are the parameters used. For the structural design, the structure parameters used are the size of the structure, and the applied loads and stresses analyzed using the matrix stiffness method.

Workability of Shale Concrete

When using shale concrete, its performance is essential. The design criterion used for the required performance and durability in its plastic and hardened states is the concrete design mix. In the performance, if the plastic concrete is not workable, it cannot be properly placed and compacted in the form to serve as a structure. Workability is the ease with which the ingredients can be mixed and the resulting mix handled, transported, and placed with little loss in homogeneity. Unfortunately, workability cannot be measured directly. To consistency of the concrete is measured by performing a slump test to detect variations in the uniformity of a mix. So the physical properties were investigated and results are shown in table 1.

Table 1. Physical Properties of Shale Aggregate from Pinabacdao Shale (PS), Catbalogan Shale (CS), Motiong Shale (MS) and Jiabong Shale (JS) compared to Conventional Aggregate (CA)

	CA	PS	CS	MS	JS
Spec. gr.	**2.40**	2.12	2.27	1.89	2.14
Fineness modulus	**2.38**	2.42	2.5	1.13	2.12
Absorption %	**0.8**	20.10	13.5	15.9	24.2

Table 1 results in a 150 mm slump in workable condition, while conventional concrete has a slump of 100 mm. This is due to the high absorption of shale aggregate. The strength of the concrete is very much dependent upon the hydration reaction.

When the concrete is stressed during the application of a load, failure may originate within the aggregate. The properties of shale samples taken from four sources have varying properties. This is due to the fact that the composition of shale which is part silt and part clay is not uniform. Shale in some places is composed more of silt than clay and in some areas there are more clay than silt particles. The higher specific gravity indicates that there are more clay particles than silt particles. Shale with a higher absorption requires more water in a concrete mixture. The high amounts of water have an impact on the finished concrete mix, therefore proper care must be taken into consideration to control and attain the desired strength of concrete. Grading the fineness of the aggregate influences the mix proportion to attain a good workability of concrete. A finer size of aggregate requires more cement as shown in table 2. Shale and gravel make up about 60 to 80 percent of the volume of concrete, and their characteristics influence the properties of concrete and therefore should meet certain requirements for it to be strong, durable and economical. Other factors considered in the concrete mix design are compressive strength, grading and quality control which are discussed below.

Durability of Shale Concrete

Durability is an important property of concrete to withstand the weathering, chemical action, and wear to which it will be subjected in service over a period of years. 50 years is the common serviceability of concrete. The designing of concrete mixtures is based primarily on the water-cement ratio theory and the absolute-volume system of calculating material amounts as shown in table 2. The water cement ratio theory states that the strength of concrete is inversely proportional to the amount of water used per unit of cement (Smith 1979). A concrete design mix is a process used to proportion the shale concrete and determine its physical properties and the performance of concrete in plastic and hardened state.

Table 2. Shale Concrete Design Mixture by Weight compared to Conventional Aggregate (CA)

Component	**CA**	PS	CS	MS	JS
Cement, %	**12**	13.47	14.86	16.93	16.11
Shale,%	**34**	29.30	26.60	27.25	27.73
Gravel,%	**48**	46.02	48.18	44.36	42.20
Water,%	**6**	11.21	10.37	11.47	13.96
w/c	**0.55**	0.83	0.70	0.68	0.87

The above design and proportion by weight of the material in terms of structural concrete produces a good workability of concrete using an average water-cement ratio design equal to 0.77. The standard water cement ratio required for normal concrete is not more than 0.55 for footing and other below grade concrete, 0.50 for interior slabs on grade and suspended slabs, 0.45 for exterior and interior concrete subjected to freezing and thawing. The result is more than the required. This is due to the fact that the absorption property of the aggregate is high compared to normal concrete.

The average proportion of concrete is 1:1.825:2.965 in terms of weight. This can be approximately translated into 1:2:3 in terms of volume of materials. Table 2 shows the mixture proportion developed considering shale, coarse aggregate, and cement properties. The required slump controlled the mixture. As shown, the water cement ratio varies from 0.68 to 0.87. Concrete with higher water content is slurry, easy to mix or is very workable but it will develop lower strength. Shale absorbs water too much so it needs more water. If this demand will not be answered, the concrete mixture becomes very harsh and the surface of the concrete may become rough. On the other hand, if concrete has a lower water-cement ratio, the concrete will be able to attain higher strength. The amount of water needed in the mixture therefore must be controlled. The attainable strength of concrete with shale as fine aggregates is shown in table 3. The attainable normal concrete strength is also shown for comparison purposes. As pointed out, as the amount of water in the mix increases, or as the water cement ratio goes higher, the strength of the concrete goes lower. The strength of concrete is usually considered its most important property. The compressive strength at 28 days is often used as a measure of strength because the strength of concrete usually increases with time. The compressive strength of concrete is determined by testing specimens in the form of standard cylinders as specified in ASTM Specification C192 for research testing or C31 for field testing. The test procedure is given in ASTM C39.

Considering the Design Mixture, the shale and little water is retained to hydrate the cement. Excess water in concrete mixes occupies space and leaves honeycombs or pore spaces when it evaporates. This makes the concrete strength lower and makes the structure susceptible to weakening and reduced capability to resist stress. If the water used in mixing the cement paste is the lowest possible amount then one can expect the maximum strength will be attained however workability will be very poor.

Table 3. Strength Properties of Shale Concrete

	Compressive Strength (MPa)	Flexural Strength (MPa)	Punching Strength (MPa)
CA	**19.35**	**5.26**	**3.45**
LS	14.2	2.60	2.43
CS	17.68	2.80	2.5
MS	16.58	2.74	2.44
JS	13.14	2.40	2.40

Table 3 is the summary of strength properties of concrete with different shale aggregates. Concrete with shale sourced from Catbalogan exhibited the highest 28th compressive strength of 17.68 MPa but it is 8.6% lower than the attainable compressive strength of normal concrete. This strength however is still within the standard structural concrete requirements for lightweight concrete which range from 10-20MPa. The punching shear strength of concrete with shale from Catbalogan is 27.54% lower than normal concrete. Punching shear has little importance in vertical building construction. It is noticeable however that the flexural strength of shale concrete is 43.93% lower than normal concrete. Flexural strength has little value in vertical construction for concrete structures that are usually reinforced by steel. Steel carries the tensile/flexural stresses and the concrete's main job is to support compressive strength.

Life cycle inventories of concrete-based products show that the concrete mixture proportion has a major influence in the total life cycle impact. Improve the mixture design may result in concrete with significantly improved performance, thus care in the mixture process is very much important.

Strength of Shale Mortar (SM)

Concrete blocks, which are sometimes known as hollow blocks or a concrete masonry units are high density rectangular bricks that are cast from cement, gravel and shale (sand) and used in the construction of buildings and suburban dwelling units. Other industrial waste materials such as cinders or bottom ash and aerated concrete are used to manufacture lightweight building blocks known as cinder blocks in the United States, breeze blocks in the United Kingdom and besser bricks in Australia. However, unlike concrete blocks, these lightweight cinder blocks have a lower compressive strength and are not advisable for use in load bearing structures. The standard concrete block dimensions in some Asian countries such as the Philippines is 16 x 8 x 4 (400 mm x 200 mm x 100 mm) to 6 inches (150mm) while a standard concrete masonry unit in the United States come in dimensions of 8 x 8 16 inches (200 mm x 200 mm x 400 mm). In European countries like the United Kingdom and Ireland, standard concrete block dimensions are 17.3 x 8.5 x 3.9 inches (http://www.dimensionsinfo.com/concrete-block-dimensions/).

Three shale sources were used namely: Pinabacdao Shale (PS), Jiabong Shale (JS), River Sand (RS) and five cement-shale ratio (1:2, 1:3, 1:4, 1:5, 1:6) were considered in this study for SM. Shale grain sizes include those passing #16 sieve as shown in table 4, passing #8 as shown in table 5 and retained #16 sieve and those retained in sieve #8 as shown in table 6. Shale-cement ratio were 1 to 2 up to 1 to 6.

Table 4. Compressive Strength of Mortar Cylinder Using Aggregates Passing #16 Sieve at 28 Days

Shale Source	Cement-Shale Mixture Compressive Strength (MPa)				
	1:2	1:3	1:4	1:5	1:6
PS	6.81	2.49	2.51	1.96	1.95
JS	7.08	4.78	2.02	2.07	2.23
RS	13.01		2.84		0.76

Table 5. Compressive Strength of Mortar Cylinder Using Aggregates Passing #8 Sieve at 28 Days

Shale Source	Mixture Proportion (Cement:Shale)/ Compressive Strength (MPa)				
	1:2	1:3	1:4	1:5	1:6
PS	6.37	4.63	2.77	1.89	2.05
JS	10.36	3.48	4.00	2.13	2.41
RS	13.01		2.84		0.76

Table 6. Compressive Strength of Mortar Cylinder Using Aggregates Retained in #8 Sieve at 28Days

Shale Source	Mixture Proportion (Cement:Shale)/ Compressive Strength (MPa)				
	1:2	1:3	1:4	1:5	1:6
PS	6.58	3.58	2.87	2.67	1.86
JS	9.76	3.99	2.61	3.01	2.77
RS	13.01		2.84		0.76

The strength of shale concrete is still lower than normal concrete. It is also noticeable that the assumption a while ago that larger size means larger strength is not consistent. Here, mortar with larger shale size (greater than #8 size) behaves worser than concrete with shale grain sizes in between size #8 and #16. The strength of Jiabong shale concrete mortar is 24.98% lower than normal concrete.

Of the two shale concrete mixtures, Jiabong exhibited better compressive strength however the said strength is 45.48% lower than mortar with river sand as fine aggregates. The mortar strength shown here can still be used for plastering purposes. Compressive strength is not a major requirement for plastering purposes. Figure 6 shows that as the amount of shale or river sand increases, the compressive strength of the mortar also decreases. It is noticeable however that shale concrete mixture with 1:6 proportions is better than normal concrete.

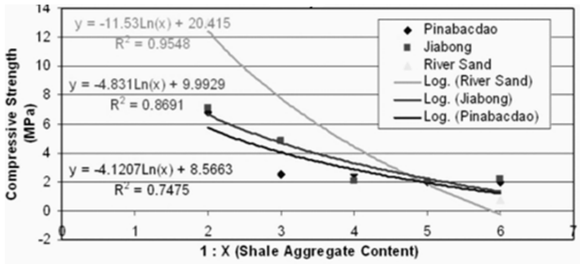

Figure 7. 28th Day Compressive Strength of Shale Concrete Mortar vs. Shale Aggregate content passing Sieve #16

Of the two shale concrete mixture, Jiabong exhibited better compressive strength however the said strength is 20.36% lower than mortar with river sand as fine aggregates. The strength was improved comparing it to the previous mixture using shale from Jiabong passing sieve #16. Figure 7 below shows that as the amount of shale or river sand increases the compressive strength of the mortar also decreases. It is noticeable however that shale concrete mixture with 1:6 proportion is better than normal concrete this behavior is similar to the previous mix. This result implies that the larger the size, the better the attainable compressive there would be.

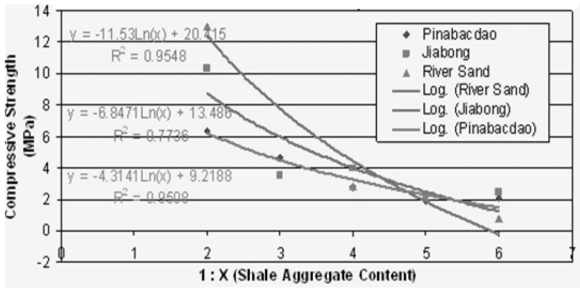

Figure 8. 28th Day Compressive Strength of Shale Concrete Mortar vs. Shale Aggregate content passing Sieve # 8 Retained in # 16

Compressive Strength of Shale Concrete Hollow Blocks (SCHB)

Two shale sources were considered in this experiment. Table 7 summarizes the properties of SCHB using different sourced SAs.

Table 7. Compressive Strength of Shale Concrete Hollow Blocks

Shale Source	Unit Weight (g/cc)	Compressive Strength (7 Days: Mpa)
PS	1.33	0.61
JS	1.32	0.66
RS	1.53	0.69

Shale samples from Pinabacdao and Jiabong were used in the making of concrete hollow blocks as these two sources exhibit higher water cement ratio. The 7 day strength is around 0.61 MPa, and 0.66 MPa for Concrete Hollow Blocks (CHB) with shale from Pinabacdao, and Jiabong respectively. CHB with river sand compressive strength is 0.69 which is close to the SCHB compressive strengths. The difference is only about 11.59% for Pinabacdao shale while it is only 4.35% lower than normal CHB.

The unit weight of CHB with shale is 13.39% lighter than CHB made of sand. This is an advantage for the weight of walls used in the calculation of applied dead loads and thereby can lower the sizes of main structures.

Shale Plaster Adhesion and Crack Assessment

Different mixes of concrete mortar considering grain size and source locations were tested and observed in this experiment as shown in tables 8 and 9. The performance and appearances of the plaster at the end of 150 days were assessed using a scale of 1 to 5. Score of 1 means that there are no visible cracks or very minimal cracks observed. A score of 1 also means that the adhesion is good. Adhesion strength was tested by tamping the surface of the plaster until it fails. On the other hand, a score of 5 means it did not appear good or it fails on the adhesion test.

Based on the results shown on table 8 and 9, the best plaster ratio is 1 is to 3 and passing #8 these is true for both shale sources. The worst mixes are those having higher cement-shale ratio.

Table 8. Mortar Properties (used as CHB plaster) Assessed at the end of 150 days Passing Sieve #16

Shale Source	ID Code	Cement-Shale Ratio	Quality Rating (1H-5L)	
			Crack	Adhesion
PS	A-1	1:3	2.5	1.5
PS	A-2	1:4	1.2	2.0
PS	A-3	1:5	4.0	2.0
PS	A-4	1:6	4.3	5.0
JS	D-1	1:3	3.0	2.0
JS	D-2	1:4	3.5	2.5
JS	D-3	1:5	3.0	3.5
JS	D-4	1:6	3.5	4.5

Table 9. Mortar Properties (used as CHB plaster) Assessed at the end of 150 days Passing Sieve #8

Shale Source	ID Code	Cement-Shale Ratio	Quality Rating (1H-5L)	
			Crack	Adhesion
PS	A-5	1:3	1.1	1.5
PS	A-6	1:4	1.5	2.0
PS	A-7	1:5	2.0	2.5
PS	A-8	1:6	3.5	4.5
JS	D-5	1:3	1.0	1.5
JS	D-6	1:4	3.8	2.5
JS	D-7	1:5	4.0	2.5
JS	D-8	1:6	4.5	5.0

Design Analysis

The shale concrete strength helped in the determination of design calculations. The design size used are the minimum requirements which are ideal for small house, type 3 of the building construction type classified under ordinary, consisting of structural concrete SC, and masonry for exterior load-bearing walls that are non-combustible construction such as SCHB are 300 mm x 300 mm column, and 300 mm x 400 mm beam, as 236 mm x 236 mm is the minimum.

Structural Column & Beam

The strength of concrete is used in the design detailing of the structure such as the size of columns and beams. The structural design is based on design parameters such as allowable stress design, dead load, live load, design strength, factored load, and duration of load. The low cost house in this study is estimated from a 30 sq. m area whose perspective is shown in figure 8. Sizes of the dimension can be further reduced if careful structural analysis is conducted. Analysis is the determination of allowable loads for simple structures. The analysis consists of determining the response of structure, loads temperature changes, and other physical action. From the result of the compressive strength of SC, the modulus of elasticity is calculated in this equation:

$$E_c = w_c^{1.5} 0.043 \sqrt{f'c} \text{ kg/m}^3 \text{ and MPa} \quad (2)$$

where E_c is the modulus of elasticity, w_c is the unit weight of concrete, and f'c is the compressive strength of concrete at 28 days. The tensile strength of concrete is much lower than the compressive strength—about 10 $\sqrt{f'c}$, lower strength concrete.

In 1918, Duff Abram established the water/cement ratio law for the strength of concrete for a frame such as the one shown in figure 9:

$$\sigma_c = A / [B^{1.5\,(W/C)}] \quad (3)$$

where σ_c is the compressive strength at some fixed age; A is an empirical constant (96.5 MPa); B is a constant that depends mostly on the cement properties (about 4); and w/c is the water- cement ratio by weight.

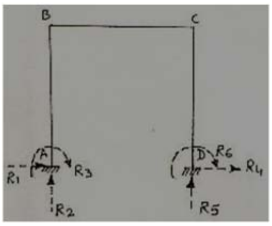

Figure 9. Structural Frame

The frame element is able to withstand bending moments in addition to compression and tension. The matrix design for every member in a rigid jointed structure will have 3 unknowns i.e (shear force, bending force, and axial force) corresponding to a 3 degrees of freedom as illustrated in equation 4. This equation will help in finding the ideal structural design one wishes to have using the results for the strength of shale concrete.

$$\begin{bmatrix} f_{x1} \\ f_{y1} \\ M_{01} \\ f_{x2} \\ f_{y2} \\ M_{02} \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_{15} & k_{16} \\ k_{21} & k_{22} & k_{23} & k_{24} & k_{25} & k_{26} \\ k_{31} & k_{32} & k_{33} & k_{34} & k_{35} & k_{36} \\ k_{41} & k_{42} & k_{43} & k_{44} & k_{45} & k_{46} \\ k_{51} & k_{52} & k_{53} & k_{54} & k_{55} & k_{56} \\ k_{61} & k_{62} & k_{63} & k_{64} & k_{65} & k_{66} \end{bmatrix} \begin{matrix} u_{x1} \\ u_{y1} \\ \theta_{o1} \\ u_{x2} \\ u_{y2} \\ \theta_{o1} \end{matrix} \quad (4)$$

Load bearing Wall

To improve insulation or reduce weight, concrete blocks are made with hollow cores such as SCHB. When used for the load bearing walls of buildings and structures, SCHB are reinforced with tie beams and concrete columns to compensate for the lack of tensile strength and to withstand seismic activity during the strong typhoons that visit the country several times a year. The hollow core is poured with cement then patched with a thin layer of concrete on both sides creating a steel reinforced concrete that increases the structural strength of the building. The exposed concrete wall surface is then covered and finished with a finished plaster. For better aesthetics, it is finished with paint. To address moisture issues and water seepage, the concrete is mixed with a water proofing additive before being poured in the hollow core of the concrete blocks.

Cost Analysis

Considering one residential building as shown in figure 10, the approximate cost of a one-story house using normal concrete ingredients in Philippine currency is about Php. 117,000.00 (2,854 USD) while the cost was reduced by as much as 17%. to Php. 105000.00 (2,561 USD) or 10% if shale aggregate is used as the fine aggregate instead of sand.

Figure 10. Proposed Prototype of SC SCHB, and SP: Cost 2,561 USD

Construction Issues & Methodologies Issues

The following construction issues are relevant in the management of SC, SCHB, SM, and SP for low cost housing.

1. Personnel training in handling the new product should be conducted, as the shale concrete requires more water, in doing so it may weaken the concrete.
2. The resource is fragile to erosion when left without cover when wet, and it expands and dries during high temperatures. Therefore stock piles should be covered. This will ensure that the aggregate will maintain the properties required to attain strength establish in this study.
3. Concreting should also be covered as excess water will lessen the strength of concrete which will weaken the structure.
4. Quality control of concrete should be maintained to get the specified result.
5. Proper care should be made in the placing of concrete so as not to let the concrete experience bleeding.

Construction Methodologies:

The following are methodologies to maximize the utilization and minimize the adverse impact to maintain a sustainable environment:

1. Shale Resource Extraction (SRE)
2. Shale Concrete Products (SCP)
3. Shale Concrete Structures (SCS)
4. Shale Concrete Installation (SCI)

Conclusions & Recommendations

As discussed above, the three axiomatic approach: Planning, Design and Construction is useful in the holistic utilization of the shale concrete (SC) for the low cost housing industry. However, behavior during actual environmental condition is not provided here and requires exploration to make a prototype and observe the behavior of the structures as loads are applied to its members and how its members respond to it. During this process, the design for re-sizing of the structures may be made.

The impact on the environment is reduced using SC, SCHB, SM, and SP, all can be classified as *green concrete* since they use technology that considers all phases of a concrete structure life cycle. This technology must include all aspects of performance such as mechanical and physical properties, workability, durability and environmental aspects. In industry, employment maybe created for local communities as an alternative livelihood employed in the extraction and refining of shale resources.

The best concretes are those with shale coming from Catbalogan. The attained strength for this concrete is 17.68 MPa for compression, 2.8 MPa and 2.5 MPa for flexure and punching shear strength and is recommended for higher structures. SC has lower strength in compression, flexure and shear than CA which is between 10-20 MPa. SCHB strength is comparable to normal CHB, however it is ideal for low cost housing as well. SCHBs which were made from PS and JS attained a 7 day compressive strength of 0.61 and 0.66 MPa respectively, while ordinary CHB has 0.69 MPa which gives a difference ranging from 0.03- 0.08. The unit weight of SCHB is about 1.33 g/cc is lighter than ordinary CHB by about 13.39%. Plaster with a 1:3 mix exhibited a smooth finish and good adhesion to the wall and can be recommended for use, while a 1:6 mix produces an ugly finished surface and very bad adhesion. The cost reduction is estimated to be about 10%.

It is recommended that a further study be made on a modular system or pre-fabricated panel as control on manufacturing of SA is safeguarded so as its strength. Also, a fiber reinforced shale concrete board (FRSCB) should also be explored. Aside from FRSCB, there are a lot more potential uses of shale, like using it for decorative blocks, paving blocks, and cornices. Other systems may also be studied such as self-framed concrete decks, long span or short span pre-cast panels or planks and bearing walls, and pre-assembled modules, prepared off or on site, for stacking or insertion in a structural frame. Finally, to further utilize the resource for high rise building and improve the current strength is another challenge to be considered.

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Design Education in Civil and Environmental Engineering

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Abstract: Design education in the Department of Civil and Environmental Engineering at MIT has been a central aspect of the curricula since 1998. This paper starts with some comments about design and design education in CEE, in general. The rest of the paper is a description of the development and implementation of the design oriented curricula in the department during the periods 1998 – 2007 (civil engineering only) and 2007 – 2013 (civil and environmental engineering). Comments on what worked and what did not are made leading to the major conclusion that developing and implementing engineering curricula should be done as a design process with integrated improvements following the principles of the observational approach.

Keywords: Design Education, Civil Engineering, Environmental Engineering.

Introduction

As in other engineering domains, design is a central activity in civil engineering and to some degree, also in environmental engineering. Nevertheless, questions arise to what extent civil and environmental engineers are involved in design. Consequently, it is necessary to think about how to best educate the civil and environmental engineering designers. Going deeper in thinking about design, it is possible and attractive to take the characteristics of design and particularly of the design process, and structure parts or the entire engineering education following the design process. This has been attempted in the civil and environmental engineering curriculum at MIT and will be described and assessed in this paper.

To achieve these objectives, general comments on design in civil and environmental engineering and design education in these domains will be made. This will be followed by a detailed description of the development and implementation of the design oriented curriculum in the Department of Civil and Environmental Engineering at MIT. The description will end with an assessment of what worked well and what did not, which in turn will be followed by thoughts on where to go; conclusions will end the paper.

General Comments on Design in Civil and Environmental Engineering

Here it is necessary to first make a few comments about environmental engineering. Many environmental engineers are involved in designing water treatment and conveyance systems or remediation of contaminated sites. By definition they "do design" and, therefore, the comments in this and the following sections apply to these activities and the corresponding education. There are, however, environmental activities that largely consist of measurement and analysis, and people doing this prefer to be called environmental scientists. This is reflected, for instance, in the MIT B.Sc. degree in Environmental Engineering Science, as well as by universities having separate departments in environmental engineering and environmental science. Although the environmental scientists play an important role in providing the basic information for environmental engineering, environmental science education is not addressed in this paper.

Coming back to "Design in Civil and Environmental Engineering", the question arises if this is different from design in other engineering domains. One of the characteristics of design is that it can be defined in different ways. One can, however, agree on the following characteristics. Design:

- Is creative
- Emphasizes synthesis (rather than analysis)
- Involves open ended/ill defined problems
- Is usually done in teams
- Is best learned by doing

These characteristics apply to any design be it designing garments, furniture, household appliances, airplanes or buildings. It may be good to mention at this point that many civil engineering designs, particularly those involving large systems are characterized by open endedness. One can also agree that the design process involves:

- Defining the problem
- Conceptualization
- Embodiment design
- Detail design
- Prototyping
- Implementation

While this process, in principle, is also used in civil engineering, there is a difference to many other engineering designs in that prototyping is usually not possible. This is often replaced by the observational approach. (Terzaghi 1961; Einstein 1991; Einstein 1997) The design consists of adaptable options; during implementation (construction) the performance is continuously observed and compared to predictions. If the observations deviate from the predictions, the design is correspondingly adapted. It is important to note that these adaptions are not done ad hoc but based on alternatives that have been designed before implementation. The observational approach is absolutely essential in areas in which the conditions are not completely known prior to implementation. This is very often so in all areas involving the subsurface (geotechnical and environmental engineering).

While what has just been mentioned is often different between civil and environmental engineering and other engineering domains, it points to something that this author considers the most important difference:

In many other engineering domains, design is a discipline often in parallel to other disciplines (e.g. manufacturing in mechanical engineering). In civil and environmental engineering, design is a fully integrated activity. Specifically speaking, one does not distinguish a structural analyst from a structural designer. This integrative characteristic goes all the way to implementation – good designers, have to fully consider constructibility, i.e. construction (implementation) has to be a part of design. This is always so in the above-mentioned observational approach but applies (should apply!) to all other aspects of engineering designs. This integrated characteristic of civil and environmental design is also essential in education.

General Comments on Design Education in Civil and Environmental Engineering

In educating future engineers, one would like to have them internalize the characteristics of design that were mentioned earlier. Ideally, this would be done by having students go through a general design education in the spirit of general liberal arts education. This has been proposed by Professor Bucciarelli (Bucciarelli 1994; Bucciarelli 2009). Such a fully integrated general design education will not only educate students in design thinking but will have them learn the essential fundamentals of natural and social sciences in this context.

A less wide ranging approach to design education is what has been implemented in MIT's Department of Civil and Environmental Engineering: It consists of a number of design oriented subjects in which the design process as described above is used to learn and apply design in typical areas such as structural engineering, geotechnical engineering a.s.o. Most importantly, students have to:

- Be creative, i.e. come up with their own ideas
- Synthesize, i.e. combine parts into an entity
- Solve an open-ended/ill defined problem, i.e. become aware of the fact that problem definition is equally important as problem solving and that there is no unique (best?) solution.
- Work in teams, i.e. truly collaborate by having to compromise, playing different roles in team meetings, be timely etc.

Although students will be made aware of and encouraged to follow the basic design process, it is most important that they learn all this by doing. "Doing" starts with simple problems and proceeds to more complicated ones; it also involves critiquing of one's work, of others' work and being critiqued. These principles were implemented in the CEE design oriented curricula.

The MIT Design Oriented Curricula

Introductory Comments

The history of what led to the design oriented curriculum in the CEE department has been described in detail by this author (Einstein 2002). Some of the most important points are briefly summarized here.

There was a growing dissatisfaction with engineering education in the United States, which became strongly apparent in the 1980's. At MIT this led to the effort by Woody Flowers to revolutionize and thus revitalize education in Mechanical Engineering. Nationally, this dissatisfaction, together with the low enrollment and retention rate of minority and women students in engineering led to the NSF funded Engineering Education Coalitions. Starting in 1990 eight such coalitions were created. ECSEL (Engineering Coalition of Schools for Excellence in Education and Leadership), which involved MIT (together with the City College of New York, Howard University, University of Maryland, Morgan State University and the University of Washington), was one of the first two of such coalitions. ECSEL used design education as the tool to improve engineering education. At MIT the leader of this effort was the Department of Mechanical Engineering but during its ten years' duration it broadened and involved all engineering departments. (This also happened at the other participating universities with different initial leads.)

Pretty much in parallel, i.e. starting in the 1990's, several faculty members in the Departments of CEE and Architecture met as a "design group" to propose and implement curricula improved through design education. This involved several efforts such as a design capping course and the modern design studio. While the capping course suffered from the fact that the teachers left MIT, the latter, conceptualized by John Williams as a modern version of the classic drafting room with intense interaction amongst students and faculty, was a success. Both the broader ECSEL activities and the internal CEE activities led to the systematic and well organized effort toward a design oriented civil engineering curriculum described in the following.

The 1998 to 2005 Design Oriented Curriculum in Civil Engineering

The systematic approach to creating this curriculum involved meetings of the entire civil engineering faculty developing the principles of three options: 1. Minor Revision, 2. Use design as integrating approach for the curriculum, 3. Eliminate traditional courses and replace them by a design studio sequence. In parallel, all faculty and most students were questioned about individual courses and the curriculum as a whole (Bush 1998). This led to the identification of weaknesses listed in table 1.

Table 1. Weaknesses in Courses and Curriculum Prior to 1998

- Students were having difficulty conceptualizing and formulating problems.
- There was little exposure to ill-defined (open-ended) problems.
- Teamwork was uncommon and ineffective.
- Coalescence was lacking; that is, sequels to courses did not rigorously rely on prerequisites. This was particularly true for some of the engineering fundamentals.
- There was not much hands-on experience, and where it did exist, there was only a limited tie-in to the associated theory.
- Courses for the most part ignored the societal context of engineering problems.
- The emphasis on abstraction and analysis gave short shrift to synthesis and creativity.
- Insufficient attention was given to communication. The writing requirements that existed were often poorly linked to the technical courses, and there was very limited use of other types of communication.

Based on all this, the second curriculum alternative was chosen but with radical changes to existing courses and creation of new courses. A total of 12 courses were developed in this context. This was done by task groups of three to four faculty members per course involving the teacher(s) of the course and the teachers relying on the course as a prerequisite. A parallel IT task group provided information on relevant IT tools. In most cases, graduate teaching assistants were involved in each task group. The entire development was coordinated by the departmental undergraduate committee and financed by ECSEL, the School of Engineering and the Department. The effort started in 1997 with three courses coming "on line" each term starting in fall 1998. Hence, the "class of 2001" was the first to run through the complete new curriculum.

The curriculum is presented in table 2. As can be seen there, the curriculum consists of a total of 14 courses. MIT has a set of institute requirements totaling 17 courses, three of which can overlap with departmental courses. Together with four so called unrestricted electives, this leads to a total of 32 courses (4 per term) for a Bachelor's degree.

Table 2. Civil Engineering Curriculum 1998

General and Civil Engineering Fundamentals:

- Introduction to Computers and Engineering Problem Solving
- Uncertainty in Engineering
- Differential Equations
- Project Evaluation
- Solid Mechanics and Solid Mechanics Laboratory
- Civil Engineering Materials and Civil Engineering Materials Laboratory

Design Course Sequence:

- Introduction to Civil Engineering Design
- Geotechnical Engineering Design*
- Engineering Systems Design*
- Structural Engineering Design*
- Civil Engineering Design

At least two of the three design courses marked with an asterisk are required.

Specialization Tracks:

- Civil Engineering Mechanics
- Civil Engineering Systems
- Environmental Engineering
- Student Formulated Track

The major new features of the curriculum were the design sequence and the specialization tracks. All courses in the design sequence were new, while the specialization tracks relied on existing courses, some with major modifications. Also entirely new were "Project Evaluation", "Solid Mechanics - Solid Mechanics Lab", "Civil Engineering Materials - Civil Engineering Materials Lab". The latter two followed the integrated philosophy of the design curriculum by putting labs and lectures together and this in the context of eventual design applications. Project evaluation was intended to provide the students with the relevant and project specific aspects of micro-economics and management.

The introductory course in the design sequence exposed students to the design process and, most importantly to learning design by doing design. A mix of hands-on projects and paper based projects, all in teams, were part of this course. The hands-on projects ranged from getting to know materials and forms in the Bauhaus tradition (see figure 1), to designing and building a coatstand (including the necessary analysis) (figure 2). The paper projects involved conceptualization and preliminary design of major infrastructure projects in the Boston area (Superfund site in Woburn, public transportation projects).

Figure 1. Form, Function, Material – Paperweight

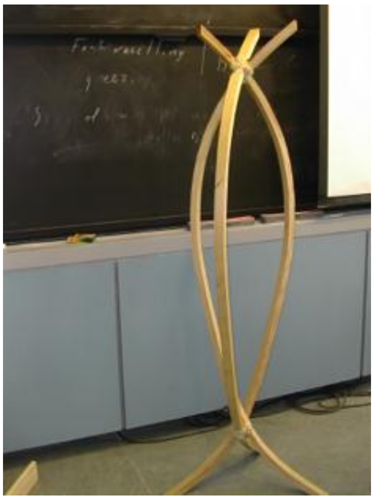

Figure 2. Coat Stand

The domain specific design courses all involved real engineering projects (e.g. bridges in the Boston area for “structures”, San Juan subway in “transportation”).

Civil Engineering Design was the capstone course. In this, the students were first sent out to critique existing structures in the Boston area – reflecting the fact that one learns design by looking at other designs. These students were also involved in two major hands-on design building experiences: Building a conceptual model of a physical process that they had to use to educate high school students, and building a 10 ft. span, 2 ft. wide foot bridge that can be easily transported and had to carry 100 lb/ft^2, i.e., a total of a ton, at a maximum deflection of l/240. In addition to having students gain extensive hands-on experience, the two projects also served essential design-education purposes: to help students understand that a) simplifications are necessary to explain complex processes in the conceptual models (figure 3) and b) details and constructibility are essential ingredients of the design-build process with the bridges. Particularly, having to design and build connections of the bridge proved to be challenging and a major educational experience (figure 4). The civil engineering design course also involved a “major design project”. This was a paper project and involved the detailed design of the infrastructure project the students had worked on in the introductory design course (mentioned above). At this point they were able to work as engineering teams on these projects with specialists in structural, geotechnical and transportation engineering. An important final ingredient to the design sequence, which had to be completed in the capstone course, is a design portfolio. All students have to present between four and six design projects that they worked on in academic courses or in summer jobs.

Overall this curriculum was a success both with the students and the involved faculty. Looking at the characteristics of design, they certainly learned design by doing design, they had to handle open-ended problems (all projects required problem definition by the students). They had to synthesize their knowledge and this increasingly so as they proceeded through the curriculum, and they were (are) very creative. The creativity was apparent in the paper design project but particularly in the built projects: The foot bridge (which is still done today) involved the building of in the order of 50 bridges over the 11 years that this was done; maybe two or three of those bridges were similar (figures 5-6).

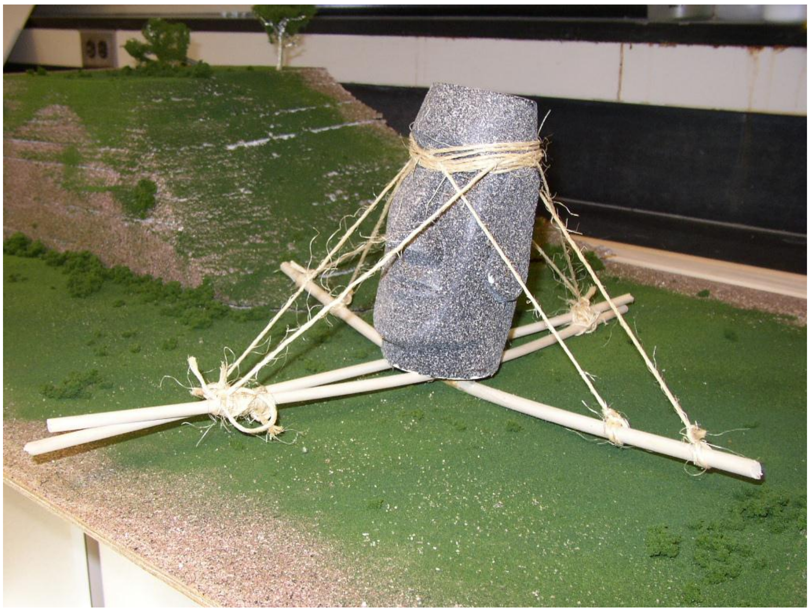

Figure 3. Conceptual Model – Moai (Easter Island) Transport

Figure 4a. Foot Bridge – Stayed Cable Bridge

Figure 4b. Foot Bridge – Importance of Connections (Bridge held weight but connection on left side failed.)

Figure 5. Foot Bridge from Styrofoam Carrying One Ton.

Figure 6. Foot Bridge Concrete Arch.

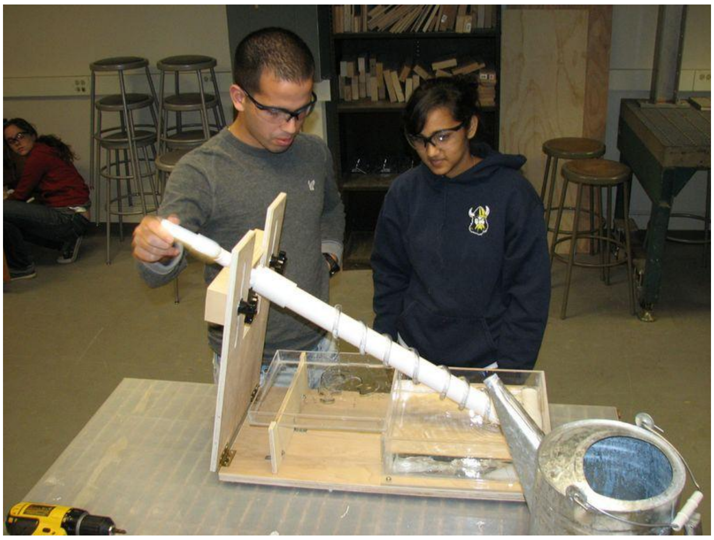

Figure 7. Archimedes Screw – Students Learn to Use Tools and Assembly Techniques.

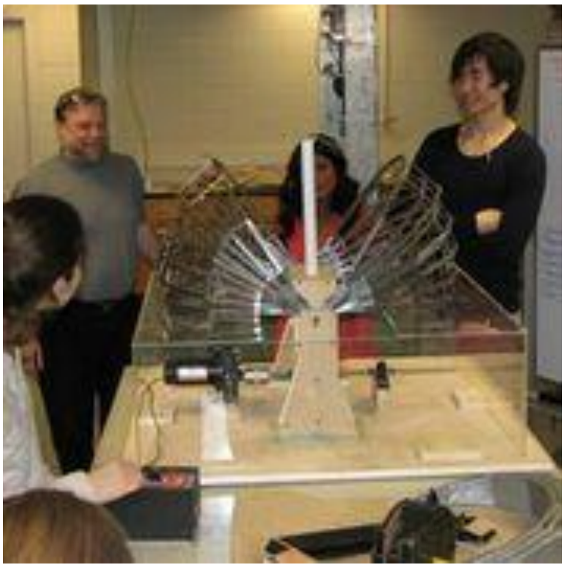

Figure 8. Demonstration Project – Foldable Roof for a Stadium/Open Air Theater.

As to be expected, not everything worked out as desired: The major design project was originally intended to be a so-called theme project with an initial design in the introductory design course, work on specialty oriented aspects in the structural, geotechnical, and transportation courses, and putting this together in the capstone course. This did not work out because of coordination problems amongst faculty colleagues and, most importantly, because the students felt they got overexposed to a particular problem. What was left was that the same project was treated in the introductory course and in the capstone course, but even this was discontinued when the curriculum was revised in 2005 (see later). Another problem was the possibility to select two of the three specialized design courses. The Department of Civil and Environmental Engineering is a relatively small department with a maximum of 20 students per year in civil engineering. Thus, selecting two of three courses meant that only a fraction of the 20 took some of the courses. While in principle not a problem, some faculty colleagues objected to having only five to six students in their classes. A related issue was that the environmental side of the department was not involved in this curriculum, and this was the main reason for the revisions and the new curriculum discussed below.

The 2005/7 to 2013 Design Oriented Curriculum in Civil and Environmental Engineering

As just mentioned, the initial design oriented curriculum was conceptualized in Civil Engineering. Starting in 2002 the work on a new curriculum involving both the civil and environmental engineering side of the department started. The actual development and gradual implementation took place between 2005 and 2007 with the curriculum in place with the academic year 2007/2008. In the following lines only the major general changes and the specific aspects covering design education are mentioned. Interested readers who want to see the details of the curriculum are referred to the CEE MIT website: http://cee.mit.edu.

The major general change was a sophomore year and a capstone class common to both civil and environmental engineering students. This was done to unify the department under the leadership of the department head (P. Jaillet). (Personnel decisions and the undergraduate curriculum are the only tools of MIT department heads to influence their departments.) The common sophomore experience consists of the courses listed in table 3.

Table 3. Common Sophomore Core in Civil and Environmental Engineering

Fall Term:

- Introduction to Civil and Environmental Engineering Design [Lab] (1/2 course)
- Ecology I
- Engineering Mechanics I (Solid Mechanics)
- Differential Equations
- One Course in Humanities, Arts, Social Sciences

Spring Term:

- Introduction to Civil and Environmental Engineering Design Lab II (1/2 course)
- Ecology II
- Engineering Mechanics II (Fluid Mechanics)
- Introduction to Computer and Engineering Problem Solving

  Or
- Uncertainty in Engineering
- One course in Humanities, Arts, Social Sciences

Design oriented courses in the new curriculum are the sophomore design laboratories listed in table 3 and the common capstone class that will be discussed in detail below. In Civil Engineering there are, in the junior and senior year, the courses on project evaluation and a transportation systems course each with equal emphasis on design and analysis. In addition, there is a combined geotechnical/structural design course in the junior civil engineering year. So while the environmental engineering students are now exposed to design (two ½ courses in the sophomore year, one capstone design course in the senior year), the civil engineering students have a somewhat reduced design experience (two ½ courses in the sophomore year, one design dedicated and two design related courses in the junior and senior year, capstone course in senior year) compared to what was done earlier.

A few comments on the sophomore design laboratories and on the capstone course are of interest: The design laboratory in the fall term starts with a brief introduction to design principles including the design negotiation game (Bucchiarelli), a paper design project similar to what was done in the earlier curriculum and significant hands-on experience. Specifically the students learn to use a variety of tools and assembly methods (saws, laser cutting, 3-d printing, gluing, bolting) with a simple project (figure 7). They also learn the basics of technical drafting. In the second half they then produce a research/demonstration project that they define, design and build in teams of four to five students. Examples range from green roofs, to wind resistant tent roofs, to geothermal wells (figure 8).

The students also have to prepare a portfolio entry i.e. the description of one of their design projects in the class that eventually will be part of their design portfolio (see earlier and below). The experiences in the fall term course allow the students to design and build much more difficult projects in the spring term (underwater vehicle with sensors, bicycles to generate power for a computer). The extensive experience with detailed design and hands-on building benefitted the capstone course. The capstone course consists of:

- Design critique of existing structure (teams of two) – This was similar to what was done before but involving also environmental projects.
- Design for natural hazards – The students select a natural hazard of interest, identify possible consequences and conceptualize design of mitigating measures.
- Foot bridge – As before (see earlier). To equally share the analytical work, the civil engineering students do the bridge analysis and the environmental students analyze a culvert. The conceptual design of the bridge and, particularly, the building is done by all students. Interestingly but not surprisingly, some of the more unusual bridge concepts came from the environmental engineering students.
- Major Design Project
- Design Portfolio (as before).

The Major Design Project is a "paper" project in which teams of up to ten students design a project. The students work as domain specialists in their teams (structures, hydraulics, etc.). The projects are not the same as in the sophomore year and they are changed every two to three years. Examples are: factory for home water treatment containers in Ghana, MIT Sailing Pavilion, vertical farms in cities, South Florida water management and revitalization in the Everglades, new building for the MIT Departments of CEE and Earth and Planetary Sciences. The students have to collect information, develop design concepts and then develop the embodiment and detailed design aspects. There are two oral presentations and a draft - and a final report.

This capstone course was co-taught by a civil - and an environmental engineering faculty member. Students who have taken it are usually very satisfied but the environmental engineering students enter with reservations because of the apparent "civil engineering" emphasis, although that usually changes through the course. Very importantly, the instructors modified the course to improve it continuously. For instance, the "culvert analysis" was added to the bridge project to more equally spread the analysis amongst civil and environmental engineering students. This was easily possible since the context (crossing a stream) is the same. We kept the common involvement in the bridge design and building because of the importance of being exposed to the integration of design and implementation. The major project underwent the most significant changes throughout the years. Originally the deliverables were an oral presentation and a final report. It became evident that students are able to do satisfactory oral presentations based on work that was not detailed or thorough enough. This became apparent in their final written reports but there was no time to change anything. We, therefore, have now a phased delivery of their design and, particularly, a draft report that undergoes detailed evaluation for substance and editorial aspects. The latter is also necessary since the capstone course is a so-called "communications intensive subject". (MIT students are required to take four such subjects, two in the humanities, arts and social sciences and two in their majors.) The modifications/improvements of the major capstone course are based on detailed surveys especially developed for this purpose. In other words, we consider the development and continuous improvement of the capstone course a design project with an observational approach - "design – implement – improve".

CEE Design Oriented Curriculum – What Worked and What Did Not

One can state pretty unequivocally that the civil engineering and environmental engineering students have significant exposure to design when leaving MIT with a bachelor's degree.

- Their work i.e. what they learned, involves the design characteristics mentioned at the beginning of this paper.
- Doing design they follow the design process.
- Through the capstone course, they are, in principle, able to integrate their design experience in various specialties, something that prepares many of the students for their careers.
- Their design portfolios allow them to show what they did in this regard.

What is not quite satisfactory is the limited design exposure students get between their sophomore year and the senior capstone course. Much of what they learn is analysis oriented. They have a strong fundamental knowledge but they get limited opportunities to apply this knowledge in an engineering project oriented context. One can argue that this is what it should be, and they will learn how to practically design through a combination of graduate school education and work in engineering practice. This argument appears to be particularly appropriate for MIT students who have the intellectual capabilities to quickly learn what is relevant. Final thoughts on all this will follow in the section below.

At this point much is uncertain because the Department is developing an entirely new undergraduate curriculum. This is still being discussed, and particularly the role of design in it is not known.

Thoughts

This author has the strong opinion, which certainly became clear through what was written so far, that design is an integral part of civil and environmental engineering and not a separate discipline. Given this fact (or opinion?) it is absolutely necessary to integrate design in the corresponding educational programs. What is actually more important is that the design process (understanding the problem, etc.) can and should serve as a framework for any educational program and for individual courses starting from the development of the course to the eventual learning process in it. It is an attractive, and by definition creative way to organize, learn and apply knowledge. Particularly, the principle of the observational approach that forces one to look at results at various stages and learn from them is an excellent way of knowledge transmittal, acquisition and digestion. Most important in using this design philosophy is the open endedness/ill definition of the “problem”: Many solutions are possible and one has to continuously and carefully look at them, assess them and improve them.

A significant issue in all this is that the design has to be taught by people doing or having done design. The selection and promotion of junior faculty today is, however, mostly research oriented. Fortunately, many of them are strongly interested in engineering design. If this were not the case, one would have to mostly rely on non-faculty practicing engineers. While having these practitioners involved is very beneficial, it would be problematic to put all the design education in their hands because it would send the entirely wrong message that design is something different than other academic endeavors.

Summary and Conclusions

The MIT Department of Civil and Environmental Engineering changed its curricula starting in 1997 to provide a design oriented education. This development initially involved only civil engineering but in 2005 was expanded to the entire department. One can conclude that the students leaving MIT with their Bachelor Degrees have learned the design principles and have been able to use them in a number of courses, culminating with the integrative design experience of the capstone course. While overall successful, it has become evident that what is done right now is the bare minimum of a good design education.

Very important is the concept that design is an integral part of all civil and environmental engineering activities and thus should be an integral part of civil and environmental engineering education. Beyond and much deeper than this are the thoughts on the philosophy of design thinking, i.e. adhering to the design principles and following the design process should characterize all educational activities from development to implementation in teaching and learning.

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Student Design to Fabrication of Wood and Steel Prototypes for a Structural and Architectural Renovation

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Abstract: It often proves difficult for engineering students to produce feasible designs, not because they lack ideas, but because they have little experience with professional fabrication or construction processes. To test this hypothesis, we had the opportunity this winter to organize a week-long, intense design-to-fabrication course at an active wood working facility: the Wood Utilization Centre of National Taiwan University Forest in Shueili. Access to a metal workshop was also available when needed. Fifteen civil engineering students with previous design experience participated in the course, supported by professional wood and metal workers. Starting from a student space renovation proposal which included a rough structural layout, the students were tasked with developing detailed prototypes of structural and architectural components. Working in groups of three, students drafted design sketches which they could immediately discuss with experienced fabricators. They then transformed their design into a full scale prototype, learning hands on as they worked the necessary steps, from wood selection to wood planing, cutting, joining, and coating. Most wood working steps were handled by the students, under the guidance and watchful eye of the professionals. Most metal working steps, by contrast, were handled by professionals following the design instructions provided by the students. By the end of the week, all five groups succeeded in producing design prototypes of good to very good quality, clearly superior to the designs produced earlier by the same students with access to a model-making lab, but without access to a real fabrication environment. Immersion in a rich fabrication environment where professionals are willing and available to work with students on their projects appears to be a powerful way for students to raise their design ability to a higher level.

Keywords: Design Curriculum, Civil Engineering Education, Design to Construction.

Introduction

Over the last three years, the Dept of Civil Engineering of National Taiwan University has been experimenting with different formulas for capstone design courses. As described in other DCEE contributions (Wu *et al.* 2011; Capart *et al*. 2013), the common feature of these experiences has been to let students work in loosely supervised teams, on a realistic design problem, targeting a specific site. The product of students' work has typically been a design proposal, described in a written report and jury presentation, possibly supported by scale models. Jury members with extensive engineering experience were then tasked with evaluating the feasibility and constructibility of the proposals. Although students often come up with imaginative proposals, and are able to present them clearly using oral and written reports, computer graphics, and scale models, construction solutions are typically unrealistic, with many problems obvious to experienced jury members that are difficult to get across to student designers without making assessments appear overly harsh.

Our latest capstone course, in the Fall 2012, let teams of students propose designs for the renovation of a student space at the Dept of Civil Engineering, including both structural retrofit and new furnishings, among which a loft structure and staircase. Using physical models of reinforced concrete portals, students developed rather good solutions for the structural retrofit component of the renovation. Their solutions for new furnishings in steel and wood, however, left architectural and construction experts shaking their heads. Although students developed imaginative proposals, these would have been costly and difficult to construct, and awkward to use in practice. Students did not prove adept at integrating construction and space utilization constraints in their designs. Although the course ended with this critical assessment, an opportunity arose to address the problems in a constructive way, by offering students a follow up course targeting specifically the issues of fabrication in wood and steel. Instead of taking place in the classroom, the course would be hosted at an actual wood working facility: the Wood Utilization Centre of National Taiwan University Forest. The facility is used to transform wood from the extensive forest managed by the university into indoor and outdoor furnishings for the NTU campus and Forest visitor facilities, and to train students from the

Department of Forestry. It has a professional staff of wood workers with extensive experience, and very complete facilities located in Shueili, Central Taiwan, including lodging and catering for residential stays.

The Centre generously offered to host a one week Winter Wood Workshop for a group of 15 student designers from the Dept of Civil Engineering. The group included nearly all students who completed the Fall capstone course, except for a few students who had competing commitments, and a few new students who were interested in joining. A metal workshop located nearby in Taichung also generously offered to provide support for the steel fabrication components of the project. Over one week, students would have the opportunity to pursue the design and construction of wood/steel furnishings in a professional fabrication environment. We present below the work performed by the students and some lessons learned from the experience.

Design Brief and Workshop Schedule

In groups of three, students were to develop a scale 1:1, true material prototype of an architectural detail for the renovated student space. The overall plan was based on capstone design proposals that evolved over the previous semesters. The version adopted was not the student version, however, but a version reworked by the course instructors in collaboration with the project architect. As illustrated in figures 1 and 2, the plan included a structural retrofit, with new wing walls strengthening existing RC frames, and a new elevated loft taking advantage of the high ceiling height. The plan drafted by the instructors was not conceived as a final design, but as a basis for distributing the brief into different design details that could be pursued by different groups. Five details were targeted by five different groups: A) the loft deck; B) the loft railing; C) the table below the loft; D) the staircase detailing; and E) furnishings (table, bench, and/or shelf) to span the new space between the retrofit wing walls. Students knew in advance which detail they would work on, and had the opportunity to think about the design options they wanted to pursue ahead of time. Issues to be addressed by each group included: 1) strength; 2) form and function; 3) constructability; 4) interface with the steel and RC structure; and 5) interface with people.

The schedule took place as follows. The Saturday night upon arrival was devoted to an overview of the Shueili facilities and a discussion of the design brief. Sunday was devoted to a guided visit of various sites of the Experimental Forest where facilities in wood and steel were constructed with the participation of the Shueili Workshop, allowing students to see multiple examples of wood and steel details in actual use. On Sunday night, students worked on digital models of their designs. Monday was devoted to training in the safe use of wood working tools, including sawing and planing machines. On Monday night, students refined the digital models of their design and identified the type and dimensions of sawed wood they would require for fabrication. On Tuesday, students selected the sawed wood they would need from the various grades and dimensions available in storage at the Workshop, and performed the first processing steps (sawing, planing, and gluing into parallelepipeds of larger dimensions). On Tuesday night, students dimensioned the steel components they would need for their assembled prototype. This was faxed to Taichung so that an order could be placed for the required metal stock.

On Wednesday, students cut the wood pieces to size, shaped them into the desired forms using power tools, hand tools and a CNC machine, and proceeded to the polishing and coating steps for the more advanced groups. On the same day, some students traveled to Taichung to direct and participate in the cutting and welding of the metal components, while others remained in Shueili to continue wood fabrication. On Thursday, wood and metal work continued, and delivery by truck of the metal components occurred on Thursday in the late afternoon.

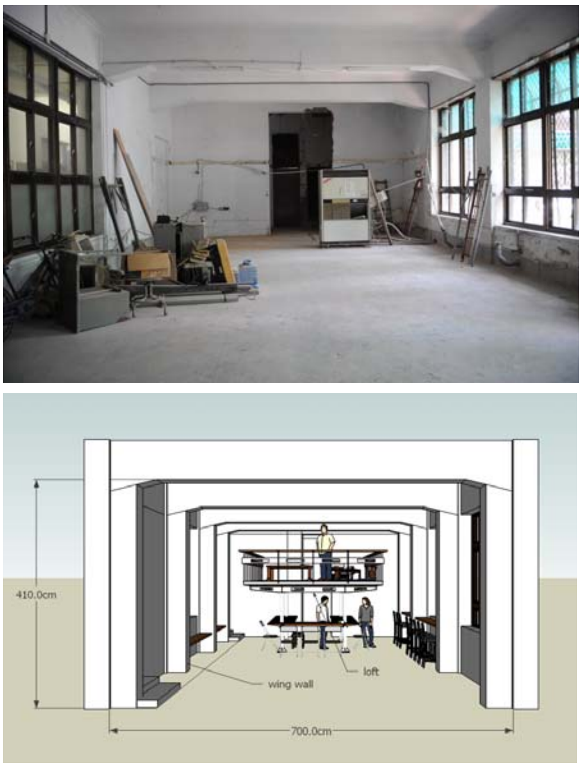

Figure 1. The Targeted Bare Space (top) and Planning Proposal Drafted by the Instructors (bottom)

Friday was devoted to fitting and assembling the wood and metal pieces together, and to painting and coating. Finally, Saturday morning was devoted to an exhibit and discussion of the finished prototypes. These were later transported to the site of the future renovated student space on the main NTU campus for exhibit and to inform the final design of the renovated space. Steps in the fabrication of the five different details are described in the next sections.

Detail A: Loft Deck

The first group of three students worked on developing prototypes of decking components for the floor of the elevated loft (figures 2 and 3). Issues to be resolved included how to design and fabricate flooring components and how to connect them with the loft structure. For this detail, the students wanted to explore different alternatives, using wood alone or a combination of wood and glass. For the wood solution, students tested whether planks could form deck elements that were stiff and resistant enough to span the 1 m beam to beam distance without intermediate supports (answer: yes).

For the mixed wood-glass solution, students developed two options: one window-like, with square glass panels supported by intermediate wood joists, and one composed of small glass panels embedded into wood planks. They found that solutions involving glass were workable, but that they would make the deck thicker relative to a pure wood solution. As the flooring panels would be appreciated from both above and below the deck, they sought solutions that would work well on both sides.

Figure 2. Loft Deck as Envisioned by the Design Brief

Detail B: Loft Railing

The second group of students developed detailed proptotypes for the railing along the perimeter of the elevated loft (figure 4). The draft design used as starting point envisioned a sparse railing system providing transparent views between the deck and lower space, without any extra functionality.

Figure 3. Design to Fabrication of Deck Prototypes. From top to bottom: students discuss their design with master wood worker; trim deck planks on the saw table; relax on the finished prototypes; present their proposed alternatives in wood only, or with glass panels to bring more light to the space under the deck.

The students of the group, however, proposed a design that would combine the functions of safety rail and book shelves. The corresponding lesser degree of transparency would provide increased privacy to the users of the loft space, who could see through the interstices between the books or by looking above the rail, but could not be so easily seen by people in the lower space.

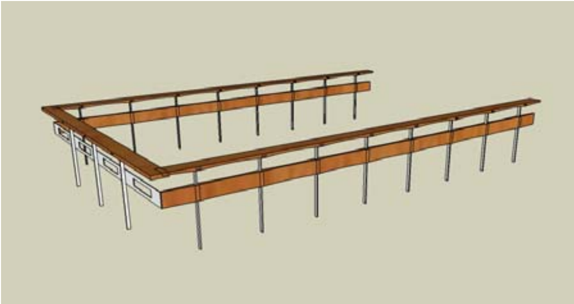

Figure 4. Loft Railing as Envisioned by the Design Brief

Lateral strength was provided by vertical steel plates, hidden within carefully adjusted pieces of wood. Horizontal shelf and rail elements were then composed of inclined wood panels, with guards to prevent books from falling off. The inclination of the top elements was chosen to let arms and books rest comfortably on their supports without sliding, yet discourage placing drinks and beverages that could be spilled on victims underneath. Students found out that adjusting the wood and steel pieces to each other was not as simple as they hoped, as imprecise welding required reshaping the corresponding wood slots. Due to unclear units, screw holes drilled at wrong locations into the steel pieces also had to be re-drilled before assembly could proceed. The workshop proved to be a good lesson on the importance of clear drawings to the fabrication process.

Figure 5. Design to Fabrication of Loft Railing. From left to right and top to bottom: students finalize dimensions with a master wood worker; carve out space for a steel plate; polish steel edges; assemble the railings which double as book shelves, as seen when the railing segments are fully assembled.

Detail C: Table Below Deck

The third group was tasked with designing and fabricating a table prototype for the space beneath the elevated deck. This table would be used both for formal meetings and for informal discussions, and would be supported by the structural columns supporting the deck. The design brief envisioned a rectangular, U-shaped table illustrated in figure 6.

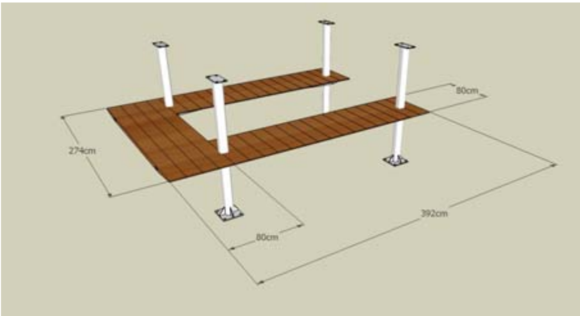

Figure 6. Table Below Deck as Envisioned by the Design Brief

The students of the group opted instead for a more curvy shape, formed from a pair of large kidney-shaped tables mounted onto the loft columns. The table prototype they built was composed of large plywood panels, cut to shape and assembled together, and covered by a thin veneer of dark wood. They proposed using a k-shaped truss to support the table and at the same time provide lateral reinforcement to the elevated deck structure.

They tested the approach by constructing a complete assembly formed of two steel columns, the k-shaped truss, and the large table resting on the truss and on handle-shaped attachments welded onto the columns (figure 7).

Detail D: Staircase Steps

The fourth group was tasked with detailing the staircase access to the elevated deck. The design brief proposed wide wood steps cantilevering precariously outward from an oblique steel beam (figure 8).

Figure 8. Staircase to the Upper Deck as Envisioned by the Design Brief

Figure 7. Design to Fabrication of the Table Below Deck. Students cut plywood panels to the desired shape; assemble and paint the steel support structure elements; mount the table onto the structure; yielding a large kidney-shaped table spanning between and around the deck columns.

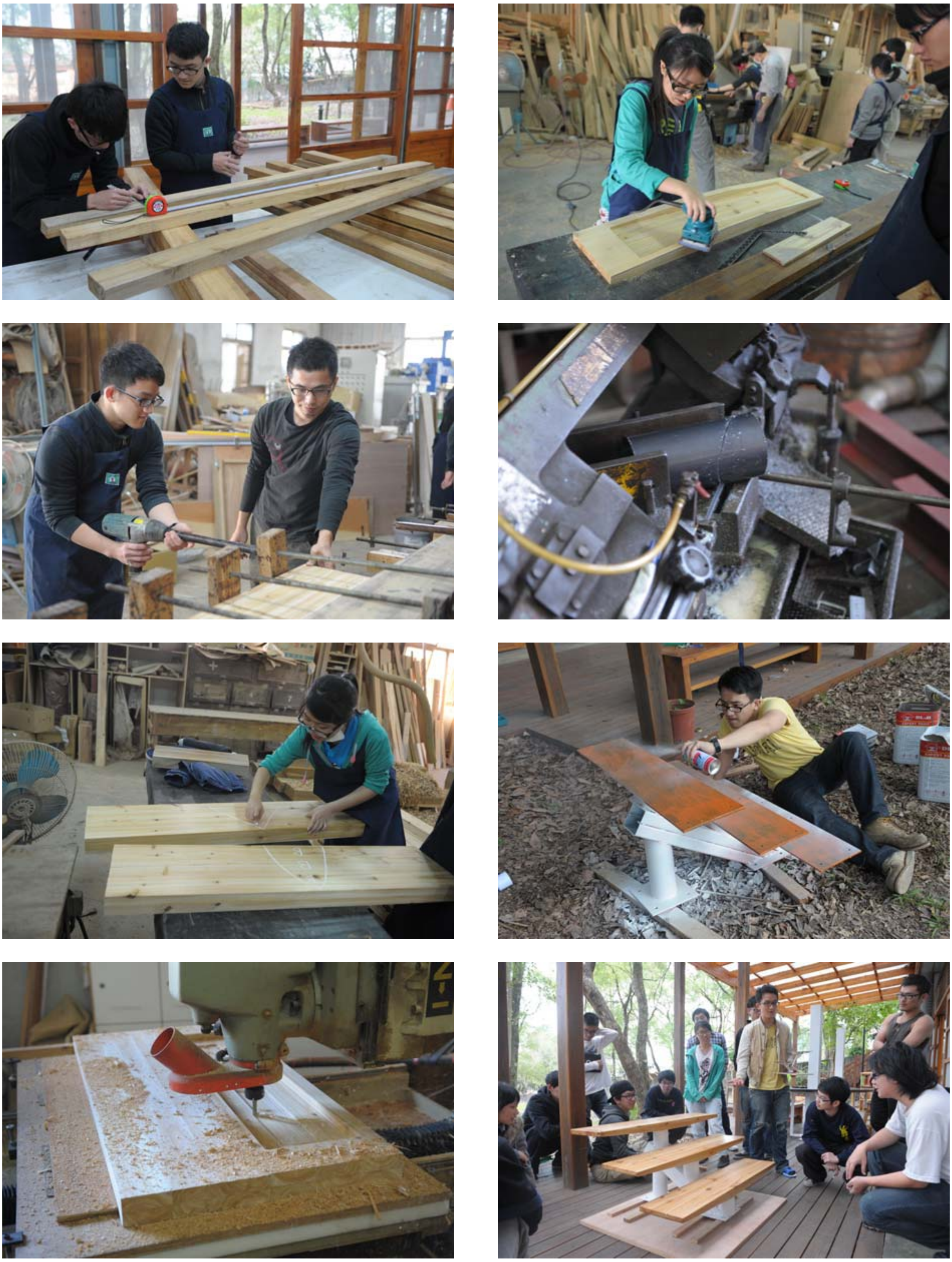

Figure 9. Design to Fabrication of Staircase Steps Cantilevering Out from Oblique Steel Beam. Left to right and top to bottom: students measure wood pieces; glue pieces together; form block from multiple pieces; carve out cavity for steel plate and ribs; polish one of the shaped wood steps; cut cylindrical steel mounts; spray paint the steel supporting structure for the prototype; present the assembled prototype during the final exhibit.

Detail E: Table Between Wing Walls

The fifth group of students was tasked with producing a prototype of a wall-facing table, suitable for mounting between the wing walls (figures 10 and 11). Students opted for massive wood blocks supported by steel ledges, with curved edges suggesting connected personal spaces. The designers envisioned a boy and a girl facing the window, working side by side on a difficult calculation, then turning to each other for discussion and living happily together forever thereafter.

Figure 10. Wall-Facing Table Between Wing Walls, as Envisioned by the Design Brief

Steel and Wood Beam

In parallel with their group work on a specific detail, students from all groups took part in to the joint fabrication of a full-size beam for the elevated loft structure, designed by the course instructors. Cantilevered at both ends, with a curved lower edge, this beam is composed of a steel T-section sandwiched between two glulam sides.

Students from different groups helped out with different stages of beam construction, whenever their own group work experienced some downtime (e.g. when waiting for the glue to dry). They also helped with other ongoing tasks at the Shueili Workshop (like furniture repair), adapting to a work culture in which everyone keeps busy.

Working in this way, it proved possible to produce the 6 m long fully functional beam in a matter of days (figure 12).

Figure 11. Design to Fabrication Wall-Mounted Table. Top to bottom: students cut a planed block to the desired dimensions; prepare to glue blocks together; cut metal ledges; present their prototypes temporarily mounted onto an outdoor concrete wall at the Shueili Wood Utilization Centre.






Figure 12. Fabrication of a Composite Steel/Wood Beam. Left to right and top to bottom: students assemble glulam pieces; pass them through the planing machine; disembark the steel T-section from the back of the truck; adjust the wood sides to the steel T-section; carry the completed beam to the exhibit site; load-test the beam.

Evolution of student designs

To help assess the impact of the workshop on the development of students' design ability, the evolution of student designs before and after the workshop is illustrated in figure 13. The top panel is an early conceptual sketch of the deck and staircase. The focus at that stage (Spring 2012) was on how users would experience the renovated space, with little to no consideration of structure and construction. The next design stage (Fall 2012) was to focus on these structural and constructive issues, and produce practical designs. As illustrated by the middle panel of figure 13, however, the designs that students evolved over that semester remained awkward overall, with little sense of structural coherence and detailing too vague to inform the actual fabrication and assembly of components. After the Winter 2013 wood workshop, students worked one more semester to revisit their designs. As illustrated by the lower panel of figure 13, the designs produced at that stage (Spring 2013) show a marked improvement across the board.

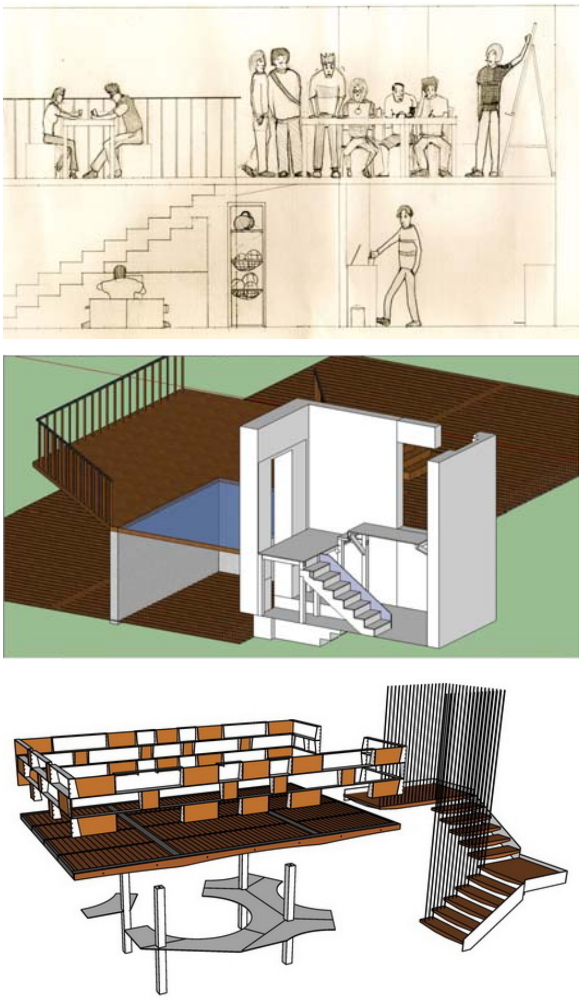

Figure 13. Evolution of Student Designs Before and After the Winter 2013 Wood Workshop. Top: Spring 2012; middle: Fall 2012; bottom: Spring 2013.

The new student designs integrate wood and steel components into a cohesive scheme that addresses both functional and structural requirements. Although the scheme is playful and interesting, its components are simple enough to fabricate and assemble economically. In addition to the rendering shown, students produced detailed construction drawings of their designs, which have provided the basis for costing and commissioning the work to steel and wood contractors. At the time of finalizing this article, the fabrication is in progress and students continue to be involved in modifying their designs to respond to issues raised by the contractors.

Discussion and Conclusions

The concerns we had prior to running the workshop included safety and relationships. Could students learn to work safely in a professional workshop environment? Would they be able to establish good working relationships with the professional wood and metal workers? The students turned out to be good apprentices, showing initiative yet responsive to guidance from the master workers. The excellent guidance and supervision they received in turn allowed them to work safely and productively over the short, intense period of the workshop.

For most of the students, this was not their first design to fabrication experience. In their first, second, and third year of undergraduate study, they had earlier pursued projects involving the construction of models and prototypes, including a wood bridge project with architecture students from Shih Chien University (see Capart *et al.* 2013). This equipped them with useful skills, but also made them aware of their own limitations, probably making them more receptive to advice from experienced practitioners.

Although approaches based on virtual collaborative environments can also help students learn how to integrate architecture, engineering and construction (Fruchter 2001), working in a real fabrication environment appears to be highly fruitful. The workshop clearly allowed students to raise their abilities and sensibilities to a new level. They received immediate feedback on their designs from experienced fabricators, but also from the tools and materials they worked with directly. At school, students are accustomed to working and reworking their designs in digital form, sometimes over periods of many weeks. Immersed in the workshop environment, they discover that design decisions become irreversible at a fast pace, as the wood gets cut and planed to their specifications. They discover that accidents of fabrication inevitably induce imperfections, but also make the result of their work alive in unexpected ways, as when veins in the wood create patterns of uncontrolled beauty.

Acknowledgments

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A New Approach to Design Education for the 21st Century

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Abstract: Design training in Architecture and Civil Engineering has long been directed towards the improvement of the educational background through a mono-disciplinary thematic learning. Nowadays, design education should offer architects and civil and environmental engineers a good opportunity to increase their planning, technological and economic skills. It should also allow the integration of different technicians, able to share their individual expertise within a team. This work presents the organization of a methodological approach for the training courses of 21st century designers. The main aim of this didactic process is to enable students to plan and coordinate all aspects through the whole design process, both at the urban scale and at the building scale. This new approach should guarantee a specialized education in an area of scientific and social relevance and create a center of excellence for training in the design field. Students would have the chance to experiment with new teaching tools for learning, in collaboration with research centers and companies in the building sector. The project management has a particular relevance in design education, and it leads all training processes across concept design, building design, construction and monitoring, and integrates the necessary tools for planning and controlling project activities during the design and the construction process.

Keywords: Innovative Teaching Methodology; Interdisciplinary Learning; Project Management in Building Process; Training and Education.

Education and Training Statistics

According to the Bologna process, the Italian University structure (figure 1) consists of three degree levels: Bachelor´s degree, Master´s degree and Ph.D. degree. There are also postgraduate specialization courses (known as first and second level postgraduate Masters) which can be attended after a Bachelor´s or Master´s degree. In addition the Italian education system provides professional courses, organized by centers for vocational training and/or higher education institutes, which do not release any education degree but diploma or certificate of attendance (Dilorenzo *et al.* 2003; EACEA P9 Eurydice 2010; Masia *et al.* 2009).

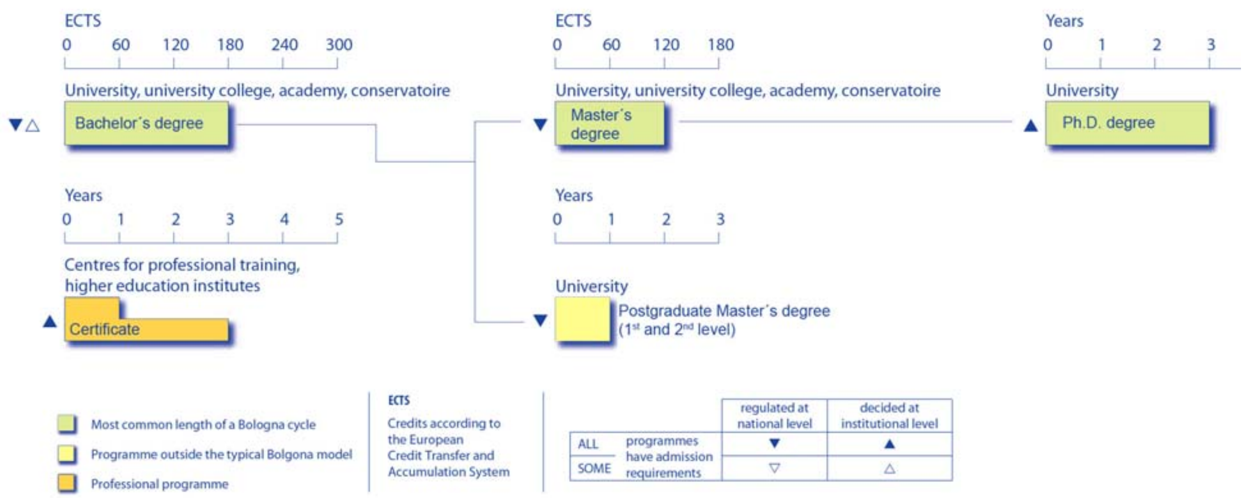

Figure 1. Higher Education Structure in Italy (Source: EACEA P9 Eurydice 2010)

Education and training are considered the highest political priority for the European Union. The possibility of acquiring and continuously upgrading a high level of knowledge, skills and competencies is considered a prerequisite for the personal development of all citizens and for participation in all aspects of society from active citizenship through labor market integration. Lifelong learning has been created as an overarching strategy for citizens to meet new challenges (Eurostat 2005).

Based on the European statistics "Eurostat", Italy is classified below the European average in the lifelong learning field. Figure 2 shows participation in adult learning by people from 25 to 64 years of age among European countries in 2012. Despite the low Italian ranking, in last twelve years (2000-2012) the participation of Italian people in adult learning has been increasing in quite a homogeneous way, excluding the years 2009 and 2011 (figure 3).

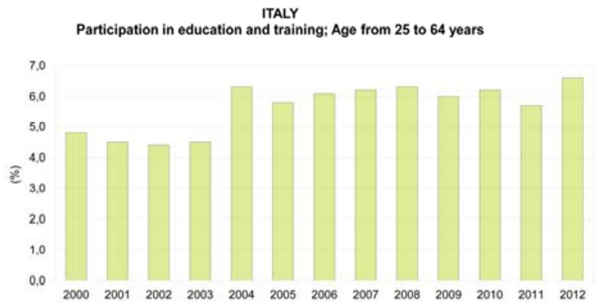

Figure 2. Participation in Education and Training by People from 25 to 64 Years of Age in European Countries (Source: Eurostat 2012)

Figure 3. Participation in Education and Training by People from 25 to 64 Years of Age in Italy (Source: Eurostat, 2000-2012)

The European statistics "Eurostat" (table 1) confirm that one out of three EU citizens with a high educational level more frequently participated in non formal education e.g. professional training courses that are not recognized by public institutions. In contrast, in Italy non formal education was followed by: one out of seven persons having a high educational level; one out of fourteen employed persons; and one out of fifty unemployed persons.

Table 1. Participation rate in non formal learning by educational level and working status in European countries; Target population 25-64 years old (Source: Eurostat 2003)

	Educational level			Working status		
	High	Medium	Low	Employed	Unemployed	Inactive
EU25	**31**	**16**	**7**	**21**	**14**	**6**
BE	35	19	9	26	13	5
CZ	27	12	4	17	6	2
DK	61	44	31	53	41	23
DE	25	11	4	16	12	4
EE	27	11	:	19	13	:
EL	13	5	1	6	7	2
ES	21	13	5	12	16	5
FR	35	20	11	25	20	6
IT	14	7	2	7	2	1
IE	24	14	7	17	12	6
CY	45	17	4	25	13	4
LV	33	11	3	17	8	4
LT	20	5	:	10	4	:
LU	36	16	5	20	20	6
HU	10	5	2	6	5	2
MT	25	23	6	14	:	4
NL	15	12	6	13	9	5
AT	45	26	9	30	25	11
PL	32	8	2	15	4	1
PT	30	18	5	11	9	4
SI	49	22	7	31	13	5
SK	41	20	7	29	7	2
FI	60	37	24	50	25	16
SE	64	45	30	53	24	23
UK	56	34	11	42	26	14

Source: Eurostat LFS, Ad Hoc module on Lifelong Learning 2003
Target population: 25-64 years old

Due to the current economic crisis which impacts employment, in Italy postgraduate Masters and professional training are often considered the best way to manage one´s own time while waiting for a job opportunity. The Italian unemployment rate is very high and this situation requires education and training support in order to provide the citizens the possibility to update their professional skills and competences and create new professional profiles.

In Italy postgraduate Masters and professional training represent the essential elements of university lifelong learning, as they are education training courses with a vocational focus. The Italian statistics from 2001 to 2006 carried out by MIUR (figure 4) confirm that the most attended postgraduate courses are professional training courses (44,4%), Ph.D. courses (22,9%), and second level postgraduate Masters (12,7%).

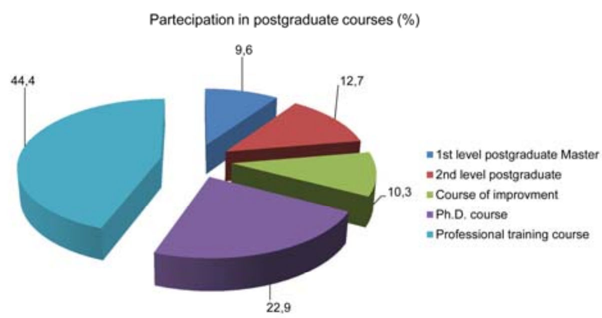

Figure 4. Participation in Postgraduate Courses by People from 25 to 64 Years of Age in Italy (Source: MIUR 2006)

Energy and Construction Industry

The quantity and the quality of available energy resources have a great impact on the development of economic systems. Moreover, energy influences the quality of people's life and the cost of products in the construction industry. In general, technological development of the modern society requires an ever-increasing demand for energy and in the meanwhile a growing awareness of the sources used for the energy production.

In the construction industry, this awareness should be held by technicians who work at every level and in every stage of the building process. When the demand for energy was significantly lower than it is today, there was no need to resort to alternative renewable low-cost energy. Nowadays, the energy situation is completely opposite and there is a lack of adequate training for technicians in the building sector, both during secondary education (professional schools), tertiary education (university) and professional career. This fact can be clearly noticed in university degree programs (architecture and engineering faculties), school curricula and professional handbooks.

The present situation of the building sector requires the connection of training and education, at every level, to the energy problems, and this circumstance should be considered at each stage of the building life-cycle process: planning (urban and building), building construction, building maintenance and management (Benedetti 2010).

1. Planning. Training and education in the planning phase should be provided at all levels and create professionals with different degrees of expertise:

- "Basic training" is offered in courses at professional schools and universities.
- "Higher education" includes Ph.D. courses and postgraduate Masters. (Ph.D. courses are offered by universities and they are not seen as vocational courses - from the legal point of view - because of their particular course structure. Postgraduate Masters are related to the university background and they are seen as vocational courses due to their link to professional world.)
- "Professional training courses" provided by associations, public and private institutions, professional bodies, professional training schools.

2. Building construction. It is necessary to underline the important role that craftspeople play in the construction industry beside traditional professional figures (the work manager, site supervisor, etc.). Although craftsmen usually do not have a higher education, they carry out relevant work related to the energy performance of buildings. The associations of craftspeople should play an active role in the promotion of training courses among associated members, so that everyone shall upgrade their know-how.

3. Maintenance and management. Maintenance and management of a building are essential to maintain the initial technical and aesthetic characteristics of the building as well as to keep its value over time. In order to guarantee higher building quality, training courses should deal with aspects related to existing buildings and energy refurbishment. Therefore, it is important to adopt a new approach to training courses with the purpose of creating a body of experts in the construction industry who are characterized by their high quality knowledge, skills and inexhaustible enthusiasm to contribute with their work not only in the construction industry, but in social progress too.

"EnergyTimber Academy"

Academy Profile

"EnergyTimber Academy" has arisen from ten year of experience in the Master in Environmental Design program at the University of Rome and in the Master CasaClima program at the Free University of Bolzano-Bozen. "EnergyTimber Academy" is a non formal education course organized by the ClimAbita Foundation with the scientific support of Fraunhofer Italia and in collaboration with companies from the construction industry. The complex structure of the Academy deals with 360 degree aspects of the building design process, and joins three main protagonists together: the ClimAbita Foundation, charged with the organization and dissemination, companies from the building sector and Fraunhofer Italia - Institute for applied research. The close relationship among these actors offers the opportunity to provide high quality knowledge and research, which improves the scientific and technological basis of students.

Academy Goals

The academy's challenge is to offer a new training approach, which should guarantee a specialized education in an area of scientific and social relevance. "EnergyTimber Academy" aims to respond to the educational needs of students, graduates and professionals and technicians in the working world, who wish to deepen their knowledge and competence related to the design of energy-efficient timber buildings. It may complete the education program of architecture or engineering graduates, freelance professionals, professionals employed in companies, industry and public and private institutions, whoever is interested in energy-efficiency in timber construction.

The innovative and vocational training program allows the creation of professional figures who are able to plan and coordinate the various aspects of design process in energy efficient projects, both at the urban and building level, paying particular attention to timber building construction and energy refurbishment of existing buildings.

"EnergyTimber Academy" is a long-term project (figure 5), which aims to create a campus and training center of excellence in the field of high-energy performance building of timber structures, which involves different figures and activities. In the course of the Academy, students will have a chance to experiment with new teaching tools for learning in collaboration with companies from the building sector and research institutes. The final focus of the didactic program provides for the construction of a small housing unit by students. These housing units, build up every year, in the following five years should create a training center and campus. It will be used in two ways: as student accommodation during training courses and as a laboratory, where companies from the building sector could test and monitor their materials and/or technology in real boundary condition and internal loads by people (Benedetti *et al.* 2013).

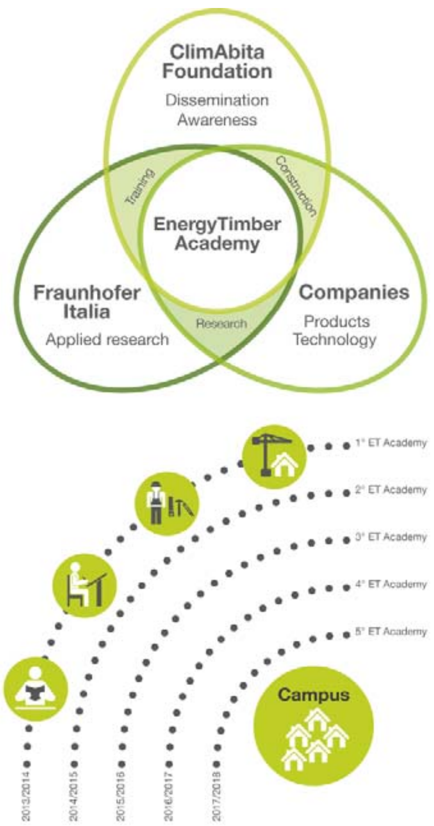

Figure 5. Concept of "EnergyTimber Academy"

Didactic Program

The Academy is a one-year course divided into modules which take place one week per month. The modules include traditional lectures, seminars and workshops, for a total of 650 hours, integrated with self-study, project and research activities (figure 6).

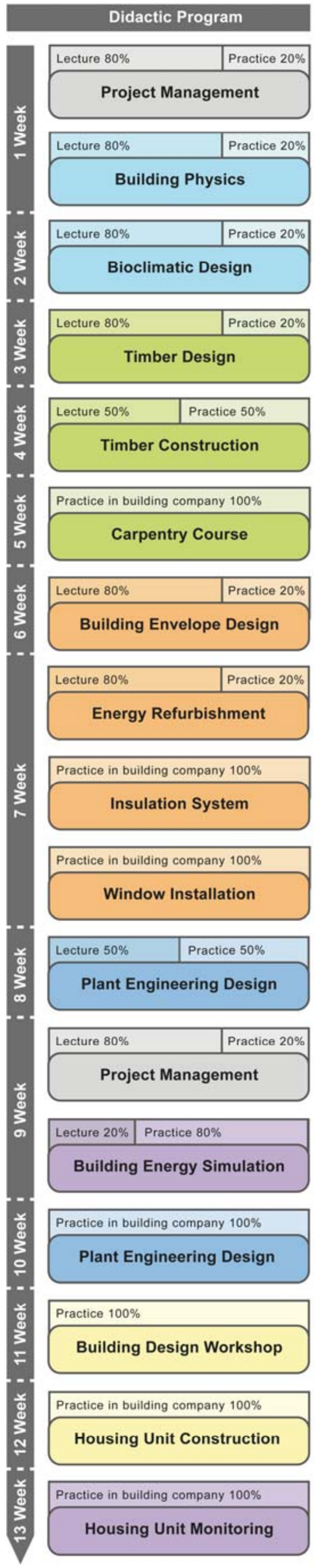

Figure 6. Didactic program of "EnergyTimber Academy"

The didactic program of the Academy, in particular, is focused on increasing the scientific knowledge, technological know-how and organizational capabilities of the participants, to encourage their entrepreneurial and innovative side. The teaching follows every scientific and building standards change and innovation that takes place in the professional sector in order to prepare students to find the right solutions to real social and professional problems. For this reason, some of the training modules are held by external experts from public administration, associations, companies and professionals who have direct experience in the building sector.

The theoretical part of the training course consists of modules related to the macro-thematic areas such as building physics, bioclimatic design, timber construction, energy-efficient building envelope, plant engineering, building energy simulation, building design workshop, construction of a housing unit in building-site and monitoring. All topics are led by principles of project management. A special focus is put on the evolution of technological systems and materials used in green buildings.

The applied part of the course includes practical activities carried out in companies from the building sector in order to put into practice the theoretical knowledge. Moreover, during the training course, participants are asked to work in multidisciplinary teams and develop together a project of a small housing unit.

Teaching Staff and Companies

The teaching staff, responsible for the theoretical part of the Academy, is composed of three main protagonists: academic professors from universities, researchers from research institutes, and professionals (architects, engineers, craftsman, etc.). The teaching staff has a long work experience in the building sector, both in Italian and international contexts. The lectures are held in English and Italian. The course provides excellent teaching, which aims to supply participants with as much input as possible. The teaching staff includes experts in their field who are motivated, helpful and available when needed.

Figure 7. Organization of Teaching Staff

The companies in the building sector are an integral part of didactic process of the Academy and have an important role in applied part of the course. The practical activities are carried out in companies and include laboratories in each of macro-thematic area of the didactic program.

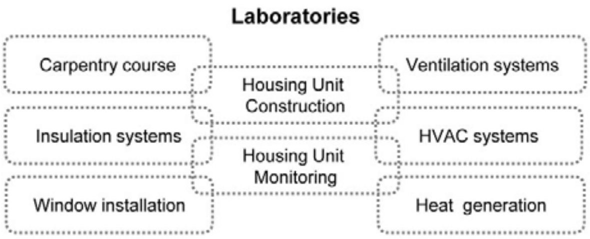

Figure 8. Practical Activities in Companies

Companies sign a contract with the Academy and collaborate as non-profit didactic partners. They are charged to hold laboratories in their head office and nominate the person in charge for teaching and organization of laboratory. Companies are supported by the didactic and scientific supervisors of "EnergyTimber Academy" in order to create didactic materials, tools and training activities.

The main partner of the Academy among the companies in the building sector is the construction timber company, who finances all construction of a housing unit. The company provides all necessary building materials, the building-site, carpenters and construction tools for students.

Moreover, all partners can benefit from the research results of the housing unit monitoring and can use the housing unit for advertising purposes, but they cannot use the students´ innovatory technology without a previous authorization of the Academy.

Student Teamwork: Strength of the Academy

"EnergyTimber Academy" aims to be a chance for participants to increase their skills, scientific and technological knowledge in the building sector. The course is suggested to:

- young graduates, who want to increase their professional knowledge before finding a job;
- professionals, who want to specialize after some years of direct experience;
- established professionals, who have enjoyed great success and challenge themselves by engaging with younger minds and new topics and approaches.

This training course requires no academic degrees for admission but some basic technological knowledge as principles of statics, design and principles of building physics are asked. This condition implies inhomogeneous background of students concerning education, work experience and expertise. Candidates will be subjected to the admission colloquium in order to select persons with a different specialization and create multidisciplinary teams.

This approach allows 20 participants to be divided into 4 groups e.g. architect, structural engineer, plant engineer, technicians and craftsman, etc., who will collaborate during the project of a housing unit. In the course of teamwork activities each of these persons should put themselves on the line and take a leading role in different skills unlike their ordinary specialization e.g. architect could be charged to structural design, plant engineer to building envelop design, craftsman to building design, etc. This group setting allows the groups to have different professional profiles that are able to cross the disciplinary boundaries and comprehend the problems of other professionals in a complex work field. The four teams are simultaneously engaged in a didactic program and project design of a small housing unit in timber construction, which is characterized by features such as energy-efficiency and flexibility of building envelope and environmental sustainability. In other words, students during the training weeks should study to absorb a new knowledge and organize a proper planning of following project activities, both in the building design and construction process. During the period between the training weeks they have to elaborate deliverables for every phase of building process, starting from the conceptual design, preliminary design, structure design, plant engineering to detail design. After 10 weeks of student collaboration the jury, composed of professors, researchers and some companies, will select the best project of a housing unit. Afterwards, during the one-week workshop all students will be joined together in one group of 20 people in order to define all details of the final project (selected by the jury) and manage a relationship with the construction company.

In the final course phase, students will construct a prototype of the housing unit, in collaboration with the timber construction company. This activity offers the participants the opportunity to practice all their skills and knowledge and to experience all problems in a building-site.

Tutors

The three protagonists of the teaching staff (academic professors, researchers and professionals) and companies (technicians) are operating in various fields of the building sector and transfer knowledge across a different educational language. In order to help the students communicate with various teaching staff members, the didactic process of the Academy is supported by tutors (academy staff). Moreover, tutors should help students to comprehend and transfer theoretical knowledge in practical field. The role of tutor is played by persons who have experience in both research and professional activities and are able to communicate with different professional figures during the didactic process, using appropriate educational language.

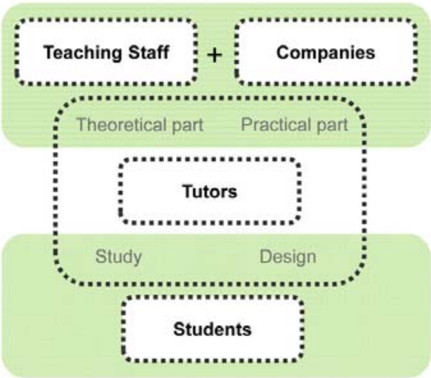

Figure 9. Tutors: connection between students and teaching staff

Project Management: The Guideline of the Proposed Approach to Design Training in Architecture and Civil Engineering

The new design education pays particular attention to project management in all its phases, from design to construction and controlling, providing all the necessary tools in order to ensure proper process planning and controlling in the building process. Traditionally problems in project performance are cost overruns, delays in planned schedules and a weak quality execution of assigned tasks (Lincoln and Syed 2011). In the “EnergyTimber Academy” course, principles from the traditional project management theory as well as innovative concepts from the “Lean Construction” field will be taught. More in detail, the focus will be set at process planning for design and construction as well as the managing and controlling of the project life-cycle. This means that concepts derived from the manufacturing industry, like the Metra Potential Method (MTM) for network planning (Kerbosch and Shell 1972) or the “pitching” concept derived from the “takt-time” principle (Rother and Shook 2009) for synchronizing different actors (planners or crafts) will be explained in an adapted form, suitable for the construction industry. Moreover, concepts from the “Lean Construction” field, especially the “Last Planner System” (LPS), will be part of this training (Ballard 2000). In order to involve every team-partner in reaching an optimal solution, these concepts will be explained within a practical approach, where the process planning, managing and controlling will be done with planning boards in teamwork. The process planning will be developed for the prototype of a housing unit which will be explained in the next paragraphs.

Housing Unit and Campus as "EnergyTimber Academy" Final Aim

The housing unit, constructed by students in the last week of training course, should become a "capacitor" of different activities as training, research and dissemination of scientific contents and knowledge.

After construction, the housing unit will be tested and monitored in order to study internal comfort, hygrothermal behavior, dynamic thermal behavior and energy performance under real boundary conditions. The one-year test and monitor of housing unit will be led by Italian research institutes, with an eventual support of a company, who provides the sensors and tools for monitoring.

Despite the housing function (student accommodation), this housing unit will be used as a laboratory unit. The flexible envelope, characterized by interchangeable elements, allows testing different materials and envelope components (insulation systems, windows, etc.). It will be a great opportunity for companies to test their innovative technologies. Moreover, the housing unit will also become a tool for the dissemination of low-energy building technologies across national and international events.

Regarding this goal, the transport of the housing unit should be easy, quick and cheap. For that reason, the housing unit has to be considered as 3-dimensional prefabricated box. In order to reach every place across Italy for dissemination purposes, the dimension of housing unit should correspond to dimension of a semi-trailer (approximately LxWxH: 13,6 x 2,6 x 3,0 m), which can be transported by truck tractor.

Conclusion

There is a great synergy between "EnergyTimber Academy" and the local economy. The actual Italian market presents a deficit of specialized professionals in energy-efficiency building design, especially in timber construction. This Academy will offer a training course, which could be a future employment source of highly-specialized professionals for enterprises, architectural and engineering companies, public administration, research institutes and so on. Furthermore, the high quality knowledge will be strictly linked with applied research activities in order to give companies in the building sector the opportunity for research, improvement and dissemination of their innovative technologies across the Italian market.

Although the building life-cycle process involves different professional figures, they usually limit activity to their own work field, without sharing experience and competences with other professionals. "EnergyTimber Academy" faces the challenge to create a group of technicians able to understand all aspects of the building life-cycle process as a whole. The participants of the training course should have the chance to cross the disciplinary boundaries, which divide the single phases within the building process and they should be able to become "conductor" in a complete and complex work field. The approach adopted by different "EnergyTimber Academy" modules should exceed the limits of the traditional education courses and train professionals able to manage the whole project in a qualified and responsible way.

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Cornerstone, Keystone and Capstone Design Project courses for Civil Engineering Students

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Abstract: Over the last three years, our civil engineering department has experimented with new courses that let students tackle design projects at various stages of their undergraduate education. Cornerstone, keystone, and capstone courses, respectively, are targeted at students in their first, second, and third or fourth year of study. Prior to disciplinary courses, cornerstone projects let students work in teams to design digital and physical scale models of architectural structures. An optional keystone course then features two intense design projects: the design and construction of a full scale wood bridge, at least 5 m in span, conducted jointly with architecture students of the same year, and the design and fabrication of a pneumatic-powered copper float. Prior to graduation, an optional capstone course aims to let students tackle more realistic design tasks on themes that vary from year to year. For the first time this year, the cohort of students taking capstone courses have earlier completed cornerstone and keystone design projects. This makes it possible to take the design process further, building upon the skills that students have acquired. The DCEE conference provides an opportunity to draw some lessons from this experience. In particular, we will try to sketch a sequence of projects which could form an organized design curriculum for civil engineering students.

Keywords: Design Curriculum, Civil Engineering Education, Design for Construction.

Introduction

Although practitioners recognize that civil engineering is as much an art as a science, the curriculum today is mostly premised on seeing our discipline as an applied science. Students are expected to learn first from theory and controlled experiments, then apply this knowledge to well-defined design problems by way of calculation. If we wish to let students gain a deeper and broader experience of the design to construction process, what are we to do? One approach is to cap the curriculum with an integrated design project, offered as a final year capstone course. A second approach is to set up a sequence of design studios starting from the first year, allowing students to gradually acquire design experience. This approach, common in architecture schools, is recommended for engineering education by Arciszewski (2009). Other experiences with integrating design and physical modeling are described by Harris and Sabnis (1999) and Solís *et al.* (2012).

Recent changes made to the curriculum at our Department of Civil Engineering offer an opportunity to compare the two approaches. Three years ago, we started to offer two types of design project courses: capstone courses, targeted at third and fourth year students, and cornerstone courses, targeted at first year students. Since then, the first cohort of first year students who took the cornerstone courses have had the option of taking a keystone design project course in their second year. This year for the first time, some of these students have now enrolled in capstone design courses. We therefore have an opportunity to compare the experience of students who have gone through a sequence of three design projects, with the experience of earlier students who were limited to a single capstone project.

At the First DCEE Conference, we presented the first edition of the cornerstone and capstone courses (Ni *et al.* 2011; Wu *et al.* 2011). In this contribution, we first describe the cornerstone, keystone and capstone courses as currently offered by our Department. We also describe how we have rearranged other elements of the curriculum to support this sequence of courses. We then contrast the experience of earlier capstone students with that of the current cohort of students, who have completed cornerstone and keystone projects prior to the capstone course. We find that students who have experienced a more integrated design curriculum have developed their abilities to a significantly higher level than earlier students. We now recruit among them the student teaching assistants who help tutor the design courses and help renew their contents, roles which used to be assigned to graduate student teaching assistants.

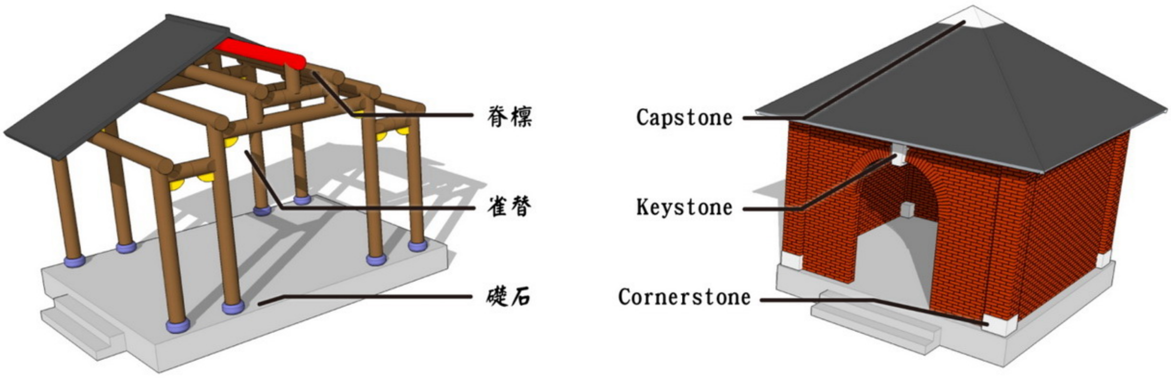

Figure 1. Terms Used for the Different Design Projects and their Motivation in the Chinese (left) and Western Architectural Traditions (right). Image designed by Chiang Yu-Chou.

The sequence of design projects currently offered in our Civil Engineering curriculum is illustrated in figure 1. Two mandatory design projects are offered in the first and second semester of the first year. They focus respectively on the design of digital and physical models. They are called cornerstone projects following the terminology adopted for freshman design projects at KAIST, Korea (Thompson 2010).

An optional keystone project is offered to second year student, and involves the design and construction of functional prototypes that exploit principles of structural and fluid mechanics.

Finally, students in their third or fourth year can take an optional capstone project course, focused on developing solutions to a realistic engineering design problem. As mandated for accreditation by the Institute of Engineering Education, Taiwan (IEET, signatory to the Washington Accord), the capstone project course will become mandatory in future years.

Figure 2. Team Design Tasks, Cornerstone Project

Figure 3. Instructor Feedback

Figure 4. Award-Winning Student Poster

Figure 5. Student Presentation of a Design Poster

Cornerstone Design Projects

Fall Digital Model Design

In the fall semester of their first year, students are tasked with their first design project: the development of a digital design for a campus improvement project. Project briefs vary year by year and have included the design of a passageway between two campus buildings, the design of an outdoor performance space, and the design of a bicycle station for the National Taiwan University campus.

On their own and during tutored design studios, students work in teams to identify and map a suitable site, conduct topographic and user surveys, develop conceptual and detailed designs, and construct a digital model of their proposed design. They present the result of their work during a poster exhibit attended by professional engineers and architects. The different stages of this process are illustrated in figures 2 to 5.

Case studies of major engineering projects in Taiwan and abroad complement the design studios. Two courses taught during the same semester provide tools used by students during their projects: surveying and engineering graphics.

Spring Physical Model Design

In the spring semester of their first year, students are tasked with the design and fabrication of a physical model of a space structure. Working in pairs, students use basic graphic statics to inform their structural design, including the configuration of rigid members and cables. They then design the geometry of their structure and the detailed joints between members using SketchUp. A computer-controlled water jet is used to cut the custom parts designed by students from 4 mm thick aluminum plates. Drilling and assembly follow, including the tensioning of cables. Mid-semester, the students load-test their structures to failure using 2.5 kg steel blocks. (The student-designed model structures are generally able to withstand up to 100 kg of distributed load.) These steps of the process are illustrated in figures 6 to 9.

Starting this year, the second part of the project introduces mechanical and electrical components, as teams of 4 students are to connect two space structures by an automated transport link. The payload is a one inch steel sphere transported back and forth. Mechanical components are again cut to student specifications using the water jet cutter. Students program an Arduino board to control electrical motors and other components. Students draw on two courses taught during the same semester: applied mechanics and computer programming.

Figure 6. Students Discuss their Evolving Design (Spring Cornerstone Course)

Figure 7. Assembly of Model Structures Made From Custom Components

Figure 8. Students Rig Their Assembled Aluminum Structure Using Steel Cables

Figure 9. Students Load Their Structure to Failure

Keystone Design Projects

During the spring semester of their second year, students are given the option of enrolling in a special version of three courses: structural mechanics, fluid mechanics, and structural and fluid mechanics laboratory. For the students choosing this option, the three courses form an integrated package built around two design projects. The first project, involving structural mechanics, is the design and construction of a wood bridge. The second project, involving fluid mechanics, is the design and fabrication of a pneumatic-powered floating copper toy.

Wood Bridge Project

This project is organized in cooperation with the Department of Architecture of Shih-Chien University. Students work in large teams of 12 participants mixing architecture and civil engineering students in their second year of study. Teams have five weeks to design and build bridges of at least 5 m span, which are to support the weight of their designers. Teams identify a suitable campus site for their bridge, develop multiple designs using scale models, load test their preferred design in the structural laboratory, fabricate bridge components at the wood workshop of Shih-Chien University, then assemble and demonstrate their full-scale bridge (figures 10 to 13).

During the wood workshop period, structural and fluid mechanics courses are temporarily suspended to allow civil engineering students to work with their architect partners nearly around the clock, as seems to be the tradition in architecture schools.

Copper Float Project

In the second part of the semester, civil engineering students work on a design project involving principles of fluid mechanics. Teams of student designers are tasked with designing and fabricating a pneumatic-powered floating copper toy. This involves the design and fabrication of hull and other components from copper surfaces, cut from copper plates using the water jet machine. The assembly is performed by soldering using a small flame.

Jets, propulsion, rotation, or other motions of the toys are alimented by pressurized air and water tanks, powered by bicycles hand pumps. The corresponding fluid circuits are assembled from copper and plastic tubing, valves, pistons and other components sourced by students from Taipei shops. This technology can be used to produce a variety of effects, dependent on the ingenuity and craftsmanship of the designers (figures 14 to 17).

Students demonstrate their toys at an outdoor pond, and document their designs using mock patent applications with English text and numbered diagrams.

Figure 10. Review of Student-Designed Scale Models

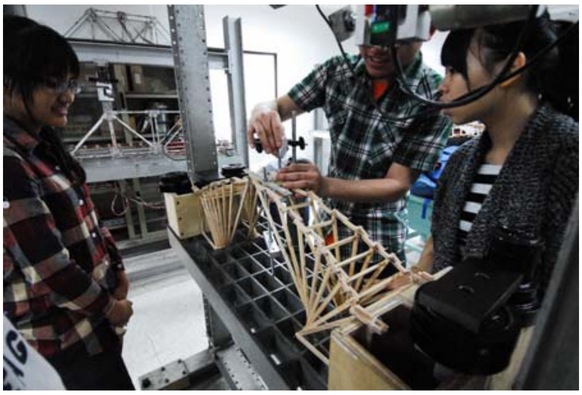

Figure 11. Load-testing of Bridge Scale Model

Figure 12. Fabrication of Bridge Components

Figure 13. Bridge Assembly and Demonstration

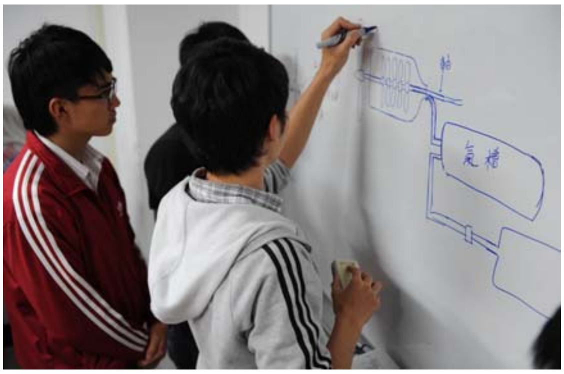

Figure 14. Copper Toy Project: Conceptual Design of the Pneumatic and Hydraulic System

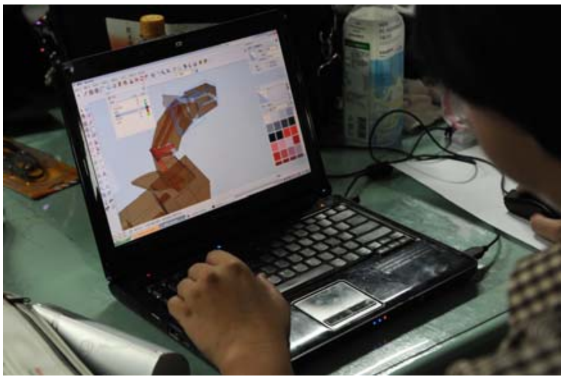

Figure 15. Digital Design of an Articulated Dragon Boat Head

Figure 16. Fabrication of the Float from Soldered Copper Surfaces and Tubes

Figure 17. Floating Copper Toy Demonstration at an Outdoor Pond on the NTU Campus

Capstone Design Project

Optional capstone design projects have been offered for the last three years, with topics that have varied from year to year. Topics have included the design of a mountain cableway, reservoir sedimentation counter-measures, alternative plans for a new Humanities Building on the NTU campus, new bridges for a flood-devastated river, and the renovation of a student space at the Department of Civil Engineering.

This last project involved the design of a seismic retrofit scheme to compensate for the removal of wall partitions in an old building constructed in reinforced concrete. To pursue this task, student teams conducted a rough evaluation of the seismic safety of the existing building based on an estimate of dead loads, member dimensions, and available information regarding the reinforcement, complemented by an exploration pit to verify the absence of transverse grade beams. They then modeled the performance of a single frame bay using structural analysis software ETABS and scale models of the frame before and after retrofit assuming different retrofit schemes. Retrofit schemes were to be evaluated based on their contribution to structural safety and compatibility with architectural plans for the renovation.

For the physical scale models, students fabricated beams and frames using a mix of plaster, sand and water to model concrete, and copper rods to approximate steel reinforcement. They conducted load testing by setting up quasi-static pull-down and push-over tests, acquiring the corresponding load-deformation curves and comparing results with hand calculations of beam responses and ETABS calculations of frame behavior. Finally, they used test results to evaluate and recommend a retrofit scheme (figures 18 to 23).

In addition to course instructors, practicing engineers advised and evaluated student designs, and recent graduates from the Department tutored the students in setting up ETABS simulations of reinforced concrete structures.

Figure 18. On Site Inspection of the Existing Reinforced Concrete Structure

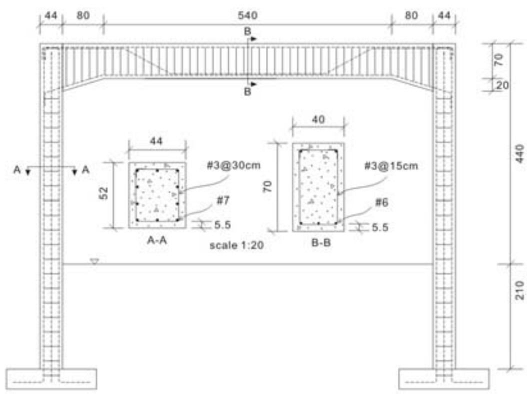

Figure 19. Tentative Frame Construction Drawings

Figure 20. Set-up of ETABS Simulations under the Guidance of an Experienced Engineer

Figure 21. Pouring of Gypsum, Sand, Water Mix into Wood Formwork with Copper Reinforcement

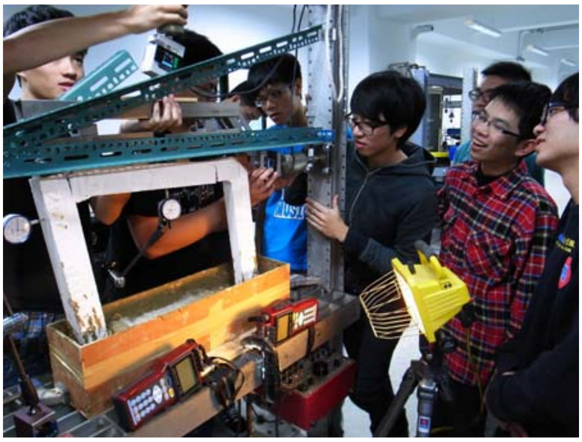

Figure 22. Pushover Test of Single Frame Bay

Figure 23. Design Review with Professional Structural Engineer and Architect

This was the first time that participants in the capstone design course had earlier completed cornerstone and keystone design projects, during their first and second year of study. This highlighted both drawbacks and benefits of the current cornerstone, keystone, capstone design curriculum. Among the drawbacks, the fact that our engineering graphics course is now directed at students in their first year means that its emphasis is almost exclusively on computer graphics manipulations and visualization. What is missing is training in drafting construction drawings. This is needed both to document existing structures and to build new ones in practice. Fluency with software is not the problem, but rather ignorance of the conventions and technology of construction.

On the positive side, students with design project experience show greater intensity in their work and a greater willingness to tackle vague problems without clear instructions. Students from previous years, without design project experience, were often paralyzed when they didn't know how to start on a task.

The improved skills of students with design project experience show up most clearly in their ability to transform their designs into functional scale models. The new students, for instance, had no problem designing wood formwork for the beam and frame scale models, and organizing fabrication from the shaping of copper reinforcement to the pouring of the gypsum concrete analogue. They tended to integrate fabrication issues early in their designs, as in the design of interlocks for their wood formwork.

On balance, the benefits clearly outweigh the drawbacks. Because the new students are fluent with the construction of digital and physical models, it is no longer necessary to devote significant chunks of time to these pursuits. Instead, the time gained can be devoted to the issues where their experience is lacking, including practical construction issues, the use of calculations to check designs, and communication with experienced engineers.

The ability to build models turns out to be a big aid to communication. Instead of seeking out professional advice with empty hands or hesitant sketches, students bring to the table their digital and physical models, and use them as first drafts to refine after consultation with experienced engineers. Because making models is no longer felt as a difficult task, they are more willing to break them and make new ones. They have also learned with the architecture students of Shih-Chien University to propose and pursue multiple solution variants to the design problems they encounter.

Whereas in previous years we relied on graduate student teaching assistants to help develop design tasks and tutor first and second year students, this year we hired undergraduate students with cornerstone, keystone, and capstone project experience (figures 24 to 27). As an indication of the abilities they have acquired, we have found that they constitute excellent tutors to younger students engaged in design projects.

Conclusion

If civil engineering is no more than an applied science, it makes sense to wait until the last year of the curriculum to let students tackle design projects. Like architecture, however, civil engineering is also an art, best experienced as a reflective practice. Students can learn this art from personal design and construction experience, reflected upon through discussion with peers and experienced practitioners. This can be aided by making design projects an essential part of engineering education starting from the first year, combined with hands-on model-making and prototype fabrication activities, and with multiple design reviews of works in the making. Here there is much to learn from architecture schools if we wish to enrich the education of future civil engineers.

Figure 24. Tutoring of a Conceptual Design Session

Figure 25. Student Tutoring at the Fabrication Lab

Figure 26. Student Tutor Presenting an Experiment

Figure 27. Student Tutor Explaining How to Use Power Tools to Dismantle a Wood Bridge

Acknowledgments

We wish to thank the TAs, student TAs, and instructors who helped design and coach the cornerstone, keystone and capstone courses. The instructors this year included Albert Chen, Chung-Che Chou, Yin-Nan Huang, Shih-Chung Kang, On-Lei Annie Kwok, Wen-Cheng Liao, and Jiing-Yun You.

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Report for Working Group 1: Design Research in Civil and Environmental Engineering

Summary by: Mary Kathryn Thompson and Irene Paradisi

Participants: Christoper A. Brown, Zbigniew Bzymek, Patrick Dallasega, Tahar El-Korchi, Shang-Hsien Hsieh, Chi-Yao Hung, Sahjabin Kabir, Lotte Bjerregaard Jensen, Marianna Marchesi, Caitlin Mueller, Pinar Okumus, Irene Paradisi, Stine Redder Pedersen, Christian Nygaard Sorensen, and Mary Kathryn Thompson

Introduction

The first 2013 DCEE working group meeting focused on issues associated with design research in civil and environmental engineering. It addressed some of the motivation for establishing design as a research discipline in CEE and some of the challenges and outstanding questions about how to do so.

Sustainability as a Driver for Civil Design

One of the major themes of the working group discussion was the increasing need for a framework to support design activities associated with civil and environmental engineering. This is being driven, in part, by the demand for more sustainable buildings and infrastructure. Energy efficiency in buildings requires the close integration of form and function. This brings the realms of architecture and civil engineering much closer than they have traditionally been. One participant noted that the "aesthetic and seemingly arbitrary decisions often make by an architect on paper during the earliest stages of design can have a huge impact on the energy performance of a building." Thus, engineers now need to participate in the design process at a much earlier stage. In addition, architects and engineers now need to work more closely together. This requires them to understand and appreciate each other's disciplines and to find a way to bridge the disciplinary divide. The establishment of a common language will go a long way to achieving this goal. But perhaps simply acknowledging that both sides do 'design' – even if that activity is substantially different in the two domains – is a start. It may also be a justification for formalizing design research in civil and environmental engineering.

Interfacing with Architects

Although there seems to be an increasing need for civil engineers, especially in the building technology domain, to interface with architects, there are some challenges in doing so. One participant noted that designers and architects are often concerned that engineers will prematurely reject ideas due to feasibility and will thus hamper the creative process. Alternately, they are sometimes concerned that the engineers will take all of the fun out of the process. How to generate the initial problem and initial concept for a building and who will do so in the future remain open questions.

There are also clear benefits to closer contact with the architecture community. Architectural design has a long tradition of exploring ideas and many techniques for supporting that process. As a result, architects regularly use history to inform modern practice. A similar technique has been used at MIT to teach civil engineering history. Participants with experience in that program reported that this improves students' experiences by allowing them to explore who has created similar artifacts in the past and how those designs were defined. History in both civil engineering and architecture provides a reservoir of strategies that can help prevent the paralysis that stems from the blank page.

Interfacing with Stakeholders

There is an increasing awareness in both architecture and civil engineering that the built environment is culturally and contextually dependent. As a result, civil and building design are becoming more participatory. This brings with it an increased need for designers to interface with various stakeholders, including the civil engineers, the construction engineers, and the end users. This may present a great opportunity for everyone, including engineers, to learn more about the initial design phase and to explore how to participate in that process in a more active and effective way.

What Does Conceptual Design Mean in the Civil Domain?

The working group participants generally agreed that the role of civil engineers in the conceptual design process must be expanded, but there was some question as to what that meant. Conceptual design involves more uncertainty than later stages of design. As a result, detailed calculations are rarely needed.

Thus, it seems that conceptual civil design may only need abstract or simplified knowledge. Perhaps only a few simple principles are needed to guide the highest level efforts? One participant asked if design research at the conceptual design phase is less about developing new technical knowledge and more about supplying and using that knowledge in a way that makes more sense. Another noted that conceptual design methods will clearly depend on the type and scale of the artifact being designed. For example, the conceptual design of a system and of a structural member will be substantially different. For the member, detailed knowledge about the material behavior will be needed at the earliest stages of design.

How to Integrate Disciplinary Research Into Design?

If more detailed knowledge from the traditional technical disciplines is needed, how is that knowledge transferred to and integrated into the conceptual design process? There are many researchers who are working on developing new technologies, materials, and construction methods to improve civil structures and systems (nano and macro aggregates in asphalt, phase changing building materials, piezoelectric pavements, etc.). How do these researchers interface with those focusing on improving the process of designing and constructing civil artifacts?

What Does the Civil Design Process Look Like?

Conceptual design is one of the earliest stages of the design process. This discussion led the working group members to contemplate the overall civil design process. It was proposed that design in civil engineering could be very similar to design in mechanical engineering from a general perspective. Thus, the design processes from that domain could be a reasonable starting point for the development of formal models of the civil design process. But there certainly are differences between the two activities, particularly during detailed design. Some of those differences include:

- Customer expectations
- Production vs. construction
- Prototyping and proof of concept activities
- Design for use and maintenance
- Life span and design for end of life

Interfacing with Existing Design Theories and Traditions

One of the questions raised by the working group was how to interface with and leverage existing design theories and traditions. Axiomatic Design (AD) Theory is the most visible example in the DCEE community because the workshop was held back-to-back with the International Conference on Axiomatic Design (ICAD) in 2011 and 2013. Is AD just a collection of knowledge? Does it only address conceptual design? What about design software? Is there (or could there be new) design software that can support conceptual design from a civil engineering perspective? How can we best utilize the tools that are already available? Can we create better ones like the program proposed by Caitlin Mueller?

Routine vs. Creative Design

During the discussion, a question was raised about the role of novelty in conceptual design and a concern was voiced about the creation of novel artifacts for the sake of novelty. The group agreed that design activities should still be classified as 'design' even if the outcome is not novel. They also agreed that novelty for the sake of novelty is wasteful and not to be encouraged. In civil and environmental engineering, cost effectiveness and the responsibility to produce sustainable artifacts often applies a pressure which overcomes the incentive to do something new. Therefore, routine, robust design is – and should be – common and valued. This implies that design research should be divided into categories that look at creative and routine design. This divide exists in mechanical engineering, but there creative design receives much more emphasis (perhaps because it is fun). In contrast, routine design must receive more emphasis in civil and environmental engineering.

Defining the Design Artifact

The working group noted that it was important to clearly define the artifact to be designed. For example, a building can be designed, the process of designing the building can be designed, and the process of constructing the building can be designed. Each of these artifacts (building or process) will have different requirements, will occur at a different phase of the larger project, and will require different expertise. One participant noted that designers and design researchers often find themselves overwhelmed by a design project because they try to design too many different artifacts at once and try to incorporate all of the requirements of all of those projects into a single set. This is particularly important because the artifacts (tools, processes, equipment, infrastructure, etc.) that are designed by one group can be used freely by other groups to take on important projects. It is inefficient and often impossible to redesign everything from scratch for every project. At the same time, it is important to acknowledge that sometimes the artifact and the process to realize it must be designed together. The goal is not necessarily to uncouple the processes or the design task but to clarify the design task to reduce the imaginary complexity.

Challenges in Civil Design

The working group participants noted that because most of the artifacts that are designed in the realm of civil and environmental engineering are unique, many of the tools and techniques from mechanical engineering and mass production do not apply. Every artifact is different and the way that each artifact is constructed is also different. Perhaps more importantly, the different suppliers and tradespeople involved in each project are different. This requires a totally different strategy for managing the design and construction process.

The working group participants noted that liability occurs on a different scale for civil and environmental engineering projects. The use of codes is necessary to protect the engineers and their firms from future lawsuits. Does this preclude truly creative design? Does it somehow change the design process? And does it introduce design research topics that are not currently addressed in the literature?

Finally, it was observed that many engineering decisions are made by non-engineering entities like the government for political, social, and economic reasons. For example, contractors who work on one large project are often forbidden from receiving the contract for a similar project in the same area to avoid corruption and encourage competition even though this is often less efficient and does not make good use of the original contractor's experience and expertise. This means that civil design is a techno-socio-economic undertaking but in a different way than mechanical design.

What Competencies Are Needed for Civil Design?

Finally, the working group briefly discussed the competencies required of a civil designer. The discussion focused on communication skills and teamwork. It was noted that the engineers need to make their knowledge and skills accessible to the designers and architectures. Graphical representation and building information modeling may be good vehicles through which to facilitate this communication.

Summary and Conclusions

Overall, the working group participants seemed very positive about the establishment of design as a sub-discipline within civil and environmental engineering. From the discussion, it seemed clear that this new domain will be informed both by mechanical engineering and by architectural traditions but that there are sufficient challenges and opportunities to justify (and require) a design perspective that is unique to CEE.

Report for Working Group 2: Design Education in Civil and Environmental Engineering

Summary by: Lotte Bjerregaard Jensen and Mary Kathryn Thompson

Participants: Christoper A. Brown, Zbigniew Bzymek, Patrick Dallasega, Tahar El-Korchi, Shang-Hsien Hsieh, Chi-Yao Hung, Sahjabin Kabir, Lotte Bjerregaard Jensen, Marianna Marchesi, Caitlin Mueller, Pinar Okumus, Irene Paradisi, Stine Redder Pedersen, Christian Nygaard Sorensen, Mary Kathryn Thompson

Introduction

The theme for the second working group was design education in civil and environmental engineering. Issues discussed during this meeting included the current state of the art of civil design education, the importance of civil design education, tools and techniques that can be used to build design competencies, the importance of balancing hard and soft skills, and the role that culture and context play and will continue to play in civil design in the future.

Current State of Design Education in Civil and Environmental Engineering

The current state-of-the-art of design education in civil and environmental engineering seems to be characterized by a lack of formalized design processes that can be taught. Frameworks, like those of Axiomatic Design Theory, Integrated Energy Design, and Architectural Design can inform civil design education. However, none are totally suitable. It seems increasingly common for civil engineering programs to experiment with design education. DCEE participants reported on several design programs which include cornerstone, keystone, and capstone design subjects. These serve both as an educational vehicle and as a platform to better understand and formalize the civil design process. However, there is an ever-present risk of simply teaching the same material to the students with increasingly difficult problems. A more formalized and deeper understanding of design in CEE would create more opportunities to teach a variety of design methods and perspectives. This would also help to develop a curriculum that would spiral outward and allow students to try out different design methods as they progress.

The Importance of Design as a Recruitment and Retention Vehicle

One working group participant noted that first year students in civil and environmental engineering are often very enthusiastic, creative, and open minded. However, these characteristics deteriorate over the course of the undergraduate program because traditional CEE curricula tend to train students to look for and provide a single solution to all problems. Exposing them to open ended problems at this point can cause them to withdraw because of a fear of proposing the ‘wrong’ solution. Therefore, it is important that students are exposed to design projects early in their engineering education so their open-mindedness and creativity remain with them throughout their careers. Another way to encourage this attitude is to expose students to design traditions and design ‘heroes’ of CEE (for example, through Bill Addis’s 3000 Years of Design Engineering and Construction). Heroes provide a legacy which is needed to gradually transform conservative professors and help students to appreciate a project-based, design approach. The historical examples also help students to develop a better vocabulary to discuss design methods in CEE.

Reverse Engineering in Civil Design Education

Reverse engineering has a long tradition in mechanical design as a vehicle to teach students about the structure of technical artifacts. Design history is often taught in architecture and sometimes also included in civil engineering education. However, increasing this type of work and having students involved more deeply by doing reverse design and deconstructing the design process may help to encourage both their analytical and design skills. For example, students can be asked to find how the design process proceeded to a certain point or to investigate alternative designs that were or could have been pursed.

Best Practices from Other Fields

Mechanical engineering and architecture provides a reservoir of design methods and educational practices which can be taught or used in CEE design courses. However, the fundamental differences between the professional circumstances should be kept in mind when they are used. For example, in civil engineering each project is (in principle) developed from scratch. In addition, in mechanical engineering design teams work with mass production as an aim, and thus more can be invested in each design process.

Defining the Competencies of Civil Designers

Much of the working group discussion focused on identifying the necessary attitudes and competencies of civil designers. For example, it was noted that professional civil engineering firms routinely stress the importance of hand sketching over computer rendering because it facilitates communication during meetings. It was also observed that civil engineers do not currently have a culture of "push back". Instead, the input from the architects is often treated as a given rather than something to be negotiated. In addition, civil engineers may need to have a greater awareness of the upstream and downstream actors in the overall design and construction process.

Cultural Context and Techno-Socio-Economic Considerations

The working group participants stressed the importance of culture and context in civil and environmental engineering and thus the need to prepare students to be culturally sensitive and contextually aware. For example, one participant noted that developing countries often do not have sufficient local expertise and so many hire consultants from abroad. Unfortunately, these engineers often do not know how to deal with the cultural differences, how to communicate with the local team, or how to appreciate the environment.

This poses a conundrum for civil and environmental design. In general, engineers do not study people while other types of designers, including architects, often do. To address these issues, the engineers must develop new competencies. However, there is insufficient room in the curriculum to add this dimension.

Multidisciplinary Design Teams

Much of the working group discussion focused on the importance of multidisciplinary design teams and preparing students to function within them. Most contemporary design processes in industry include collaboration between different professions to some extent. However multidisciplinary design processes do not take up much space in most CEE curricula.

In the US, the engineer is a consultant to the architect, not a partner. Traditional CEE curricula train the students for this professional role. As a result, most CEE students will never experience a multidisciplinary design process before they graduate. This has consequences for the professional design processes later on; most new civil and environmental engineers have no experience in how to influence the design processes, especially in the early stages. On a more positive note, there is a strong tradition of civil and environmental engineers as partners in a design team instead of as consultants in specific offices like Arup, Buro Happold, Schlaich Bergermann and Partners, etc.

Teaching civil and environmental engineers to collaborate in multidisciplinary teams is best done in actual collaboration. Architects are one of the major groups of potential collaborators for civil and environmental engineers. Developing shared projects between schools of architecture and CEE programs is an obvious possibility. The Technical University of Denmark and National Taiwan University both have experience doing so. However, research in the field is needed to determine, for example, how the first meeting between engineers and the architects should be organized. How can they avoid slipping into traditional roles where the architects create ideas and engineers optimize?

A succesful multidisciplinary design process is very dependent on attitudes and people skills. It is well known that collaborative design projects can serve as a vehicle for teaching and developing soft skills (communication, teamwork, project management, etc.) in engineering students. Collaborative personal skills can also be subject to a progression in the curriculum. For example, curricula can be extended to include international experiences and other cultural contexts.

It was observed that a new multidisciplinary common ground is being developed by the fact that the same set of simulation tools are being used simultaneously by different groups of professionals for different purposes. Having a common set of tools can enhance the communication skills of the students and help them to better understand each other's work.

Recommendations

The working group made two recommendations. First, a mapping of the design methods that are relevant to CEE should take place. The DCEE forum provides a platform where research in design education in CEE could take place and the methods appearing from the mapping could be tried out. Thus, this would be a suitable venue to undertake that mapping. Second, the working group recommends that further research in multidisciplinary design processes in CEE be undertaken and used to form the basis of more projects with this focus in CEE curricula.

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